DTU Wind and Energy Systems

Modelling of reactive power and voltage control of hybrid power plants

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Abstract

Renewable-based Hybrid Power Plants (HPP) present several advantages in front of stand-alone power plants, such as higher capacity factor, better use of the transmission and/or distribution networks or enhancement of flexibility and controllability of the assets. However, they also present challenges, such as financial or legal uncertainty and technical complexity.

In the last years, researchers worldwide have addressed the technical complexity of modelling and controlling renewable-based Hybrid Power Plants (HPP) by developing dynamic models to understand the interaction of different assets and how to produce effective control architectures, with diverse purposes. Extensive effort has been dedicated to active power controllability and frequency regulation, but little research had focused on voltage control and reactive power so far.

In this context, the project develops a novel control architecture to coordinate wind turbines, solar PV inverters, electric batteries and a STATCOM to deliver a fast reactive power response to amend voltage imbalances in the power grid. The location of the STATCOM is carefully chosen to maximize the reactive power capability of the HPP. An On-Load Tap Changer (OLTC) transformer is implemented to connect the HPP to the export line.

Three scenarios are used to explore how different degrees of ownership of the grid (OLTC transformer and export line) impact the reactive power capability and voltage control controllability. The model is implemented in MATLAB/Simulink using the Simscape Electrical environment. The results show that the OLTC is a fundamental tool to enhance the reactive power capability of the assets and that the technologies used are quite flexible in terms of voltage control, but a STATCOM with a capacity of around 8-12

Acknowledgements

This Thesis has been possible thanks to the guidance and support of professors Kaushik Das, Poul Sørensen and Anca Daniela Hansen. They have guided me since the very beginning of the project, where I barely knew the concept of Hybrid Power Plant and all their inherent benefits and challenges.

We all worked together in defining the objective and scope of the study, which was actually one of the most challenging issues of the project, since I had some ideas which needed to be shaped into something practical, interesting and exciting. They all were there to assist me with this and whenever I needed help at later stages of the work.

I would like to dedicate a special mention to Kaushik, who has been very close to me and gave me a hand at any time needed. I felt his support and confidence during the whole development of the Thesis, which kept me motivated to spend time and effort in producing a solid work.

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Lastly, I want to thank all my friends in Denmark: Vicente, Elvira, Jorge, Olivia and Constantine, who have watched my sweat and tears for these last months and have been so kind to care about me.

Contents

List of Acronyms

Acronym	Meaning
aFRR	Automatic Frequency Restoration Reserve
CAPEX	Capital Expenditures
CSP	Concentrated Solar Power
DEVEX	Development Expenditures
DSO	Distribution System Operator
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators
EPC	Engineering, Procurement and Construction
EU	European Union
f	Frequency
F	Farad (unit for capacitance in the International System of Units)
FCR	Frequency Containment Reserve (Primary Frequency Reserve)
FFR	Fast Frequency Response
FRT	Fault Ride-Through
GHG	Green House Gas
GSC	Grid-Side Converter
H	Henry (unit for inductance in the International System of Units)
HPP	Hybrid Power Plants
MPPT	Maximum Power Point Tracking
MSC	Machine-Side Converter
NREL	National Renewable Energy Laboratory
OLTC	On-Load Tap Changer
OPEX	Operation Expenditures
P	Active Power
PCC	Point of Common Coupling
PF	Power Factor
PI	Proportional Integral (controller)
PIB	Plant Interconnection Bus
PoC	Point of Connection

Acronym	**Meaning**
PPM	Power Park Modules
PV	Photo-Voltaic
Q	Reactive Power
RoCoF	Rate of change of frequency
RES	Renewable Energy sources
RfG	Requirements for Generators
S	Apparent power
SIL	Surge Impedance Load
SPP	Solar Power Plants
STATCOM	Static Synchronous Compensator
TSO	Transmission System Operator
V	Voltage
Var	Volt-Ampere Reactive
VRP	Voltage Reference Point
VRT	Voltage Ride-Through
WPP	Wind Power Plants
Ω	Ohm (unit for resistance in the International System of Units)

1 Introduction

1.1 Background and motivation

Power systems are experiencing a deep transformation worldwide. One of the main aspects of such transformation is the diversity of power plants. Traditionally, electricity was provided by few, large conventional generators that made use of fossil fuels such as coal, gas or oil. However, these conventional plants are being replaced by multiple distributed, renewable-based generators. This transformation is motivated by environmental concerns, such as reducing the Green House Gas (GHG) emissions associated to the energy sector; and economic interests, such as improving energy independence and cutting the costs of electricity generation.

To illustrate this transition, Figure 1.1 exhibits the global annual investments in the renewable electricity sector, categorized by technology. It shows that annual global investments in renewable electricity stabilized around $300 billion between 2014-2019, of which approximately 95% were dedicated to wind and solar power.

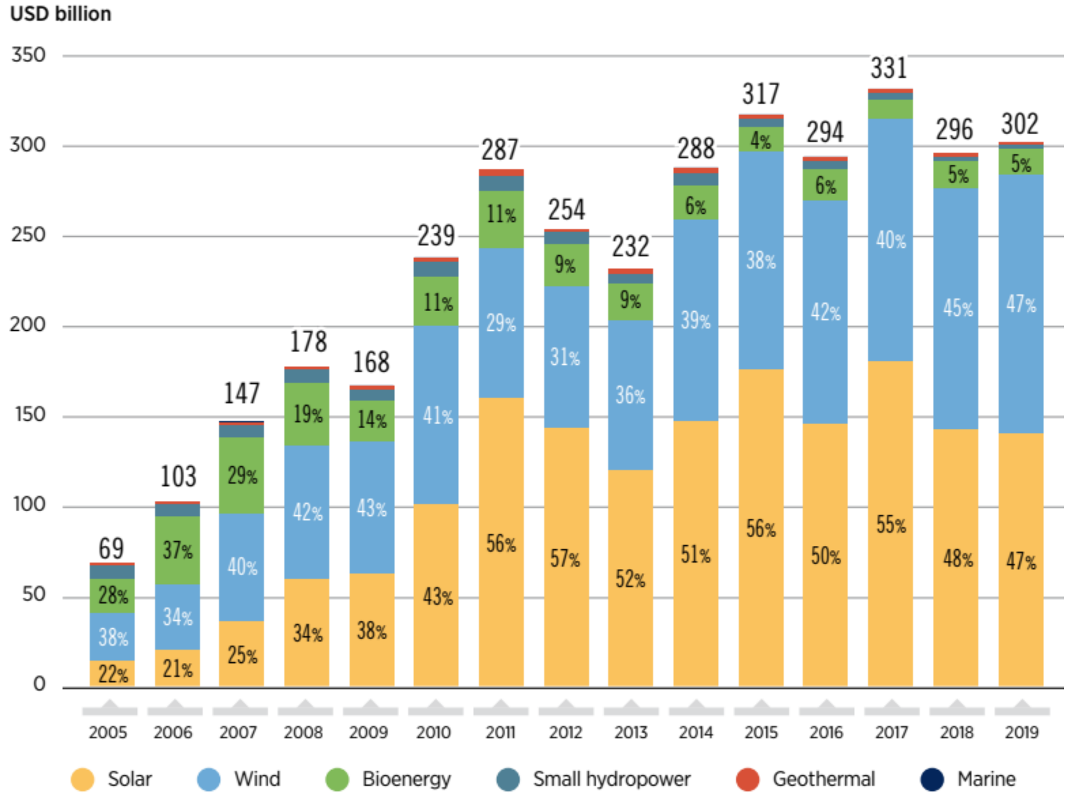

Figure 1.1: Global annual renewable energy investments by technology, 2005-2019 [1]
. Taken from .

To complement this idea, Figure 1.2 displays the new installed renewable and non-renewable capacity (left axis) and the share of renewable capacity (right axis) between 2001-2020. The blue line proves how the share of renewables has been on the raise since the beginning of the century.

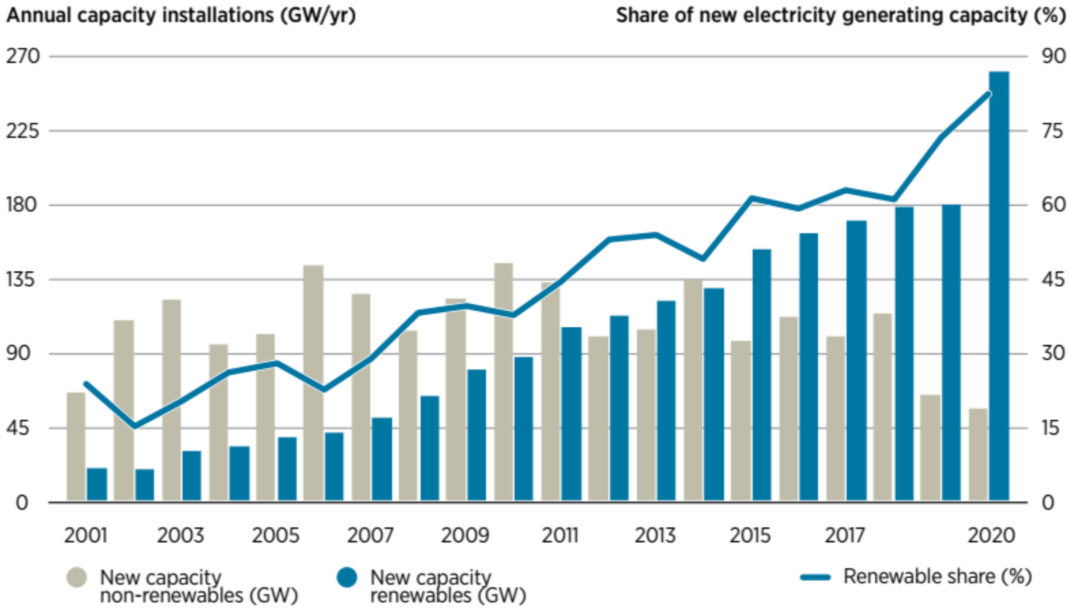

Figure 1.2: Global annual renewable energy investments by technology, 2005-2019 [1]

The energy transition is not over yet, and more and more countries are incorporating the installation of large renewable capacity in their strategic plans on the energy sector. This is the case of most National Energy and Climate Plans in Europe, such the Italian [2], Spanish [3], French [4] or German [5] ones, which are aligned with the European Commission directives [6].

Other examples of supporting policies for Renewable Energy Sources (RES) are the Australian Renewable Energy Regulations 2001 [7] or the American Energy Policy Act [8]. In few words, all these plans include policy incentives for the construction and operation of renewable-based power plants, which will keep enhancing the investments in RES in these countries.

It seems clear then that most of the new capacity to be installed in the upcoming years will be renewable-based, such as Wind (WPP) and Solar Power Plants (SPP). These technologies are leading the transition thanks to their technical maturity and low costs. However, high penetration of RES in power systems comes with several challenges, especially with regards to power quality, reliability and stability.

Some of the main challenges are:

- Decrease in system's inertia due to the use of power converters, which decouple the generator's frequency from the grid's frequency [9].
- Variability and uncertainty associated to Variable Renewable Energies (VRE), such as wind and solar, increase the need for balancing services [10], and threaten system's stability.
- The reliability of power systems with high renewable penetration can be compromised, especially in isolated systems such as islands. This creates a greater need for storage to provide a reliable service [10].

In this context, Hybrid Power Plants (HPP) can contribute to the integration of RES while addressing all their inherent challenges. But before talking about the benefits of HPP, the definition and scope must be introduced.

1.1.1 Definition of Hybrid Power Plant

Since it is a *relatively* new trend in the fast-growing energy field, the concept of Hybrid Power Plant (HPP) still needs standardization. Researchers and organizations make use of this term to refer to power plants with different topologies and technologies involved. To illustrate this lack of concordance, the definitions of two very prestigious research organizations are presented below:

- *"Power-generating facility that converts primary energy into electrical energy and which consists of more than one power-generating modules connected to a network at one connection point."*. This is Wind Europe's interpretation of HPP, as per [11].
- "*Power plants that contain two or more energy generation sources such as wind turbines, Photo-Voltaic (PV) solar, Concentrated Solar Power (CSP), geothermal power, hydropower, biomass or even natural gas, oil, coal or nuclear power."* This is the meaning of HPP for the National Renewable Energy Laboratory (NREL), as per [12].

When comparing both explanations, it is remarkable how Wind Europe includes one important requisite which is missing in NREL's definition: the connection of all the assets to a single Point of Connection (PoC) with the grid . While for Wind Europe an HPP needs to have all the individual assets connected to the same PoC, NREL considers the possibility of having a virtual connection, by means of telecommunication systems. HPPs with the former topology are also referred to as "Co-located HPP". Figure 1.3 depicts both configurations for comparison. In the remain of this report, Wind Europe's definition will be adopted when mentioning HPP.

1.1.2 Benefits and Challenges of Hybrid Power Plants

Several researchers have studied the motivations and drawbacks of HPP, and they have provided valuable arguments to contemplate whether combining technologies can be useful for owners and grid operators, and under which circumstances. At first, it is essential to consider that most of the relevant benefits derive from the possibility to install more power than the export capacity authorized by the Transmission System Operator (TSO). This may come with a high cost, since overplanting[1] can potentially lead to energy curtailment, which becomes greater with higher degrees of oversize. However, energy curtailment can be partially or fully avoided by selecting a good site, where the RES to be utilized are negatively correlated[2], and by properly sizing the HPP, which is done by means of a complex optimization process, as described in [14]-[15]. After considering this, the main advantages of HPP are listed below, as described in [11],[16]:

- **Optimization of the use of the grid.** The grid can achieve a higher degree of utilization if larger capacity than the stipulated in the connection agreements is installed. This optimizes the use of the grid and defers further investments in reinforcements.
- **Increased capacity factor.** When combining negatively correlated resources and overplanting, the overall capacity factor of the HPP is higher if compared with the same installed capacity split in individual power plants.
- **Lower costs in the PoC.** Having less authorized export capacity than installed capacity reduces the total costs associated to export permissions and infrastructure.
- **Better use of the land.** For certain configurations, combining several technologies can bring a more efficient use of the land. For instance, in WPP there needs to be long distances between each turbine where PV panels, inverters and batteries could be placed.
- **Synergies.** Developers can harvest synergies within different stages of the projects, leading to a reduction of Development (DEVEX) Capital (CAPEX), and Operation (OPEX) Expenditures.
- **Higher controllability and reduction of forecast error.** When incorporating batteries, HPP using Variable Renewable Energy (VRE) can correct deviation between actual and committed generation due to errors in forecasting, enhancing greater controllability. This opens the door to expanding business possibilities, such as the participation on ancillary services, which could increase the market value of the plant.
- **Prevention of energy curtailment.** Overplanting can be done not only in HPP, but also in stand-alone power plants. However, in the latter case energy curtailment can reach unacceptable levels. When making use of negatively correlated resources and properly sizing the HPP energy curtailment can be very limited. This can

[1]Overplanting means installing larger capacity than stipulated in the connection agreement with TSOs [13].

[2]Negative correlation of energy sources means that at times when one of the resources has potential to produce large amounts of energy, the other one has limited potential, and vice versa. For example, a site where the wind tends to blow faster at night normally shows a negative correlation between wind and solar resources.

be further improved by incorporating batteries that capture energy which would otherwise be wasted in times of high generation.

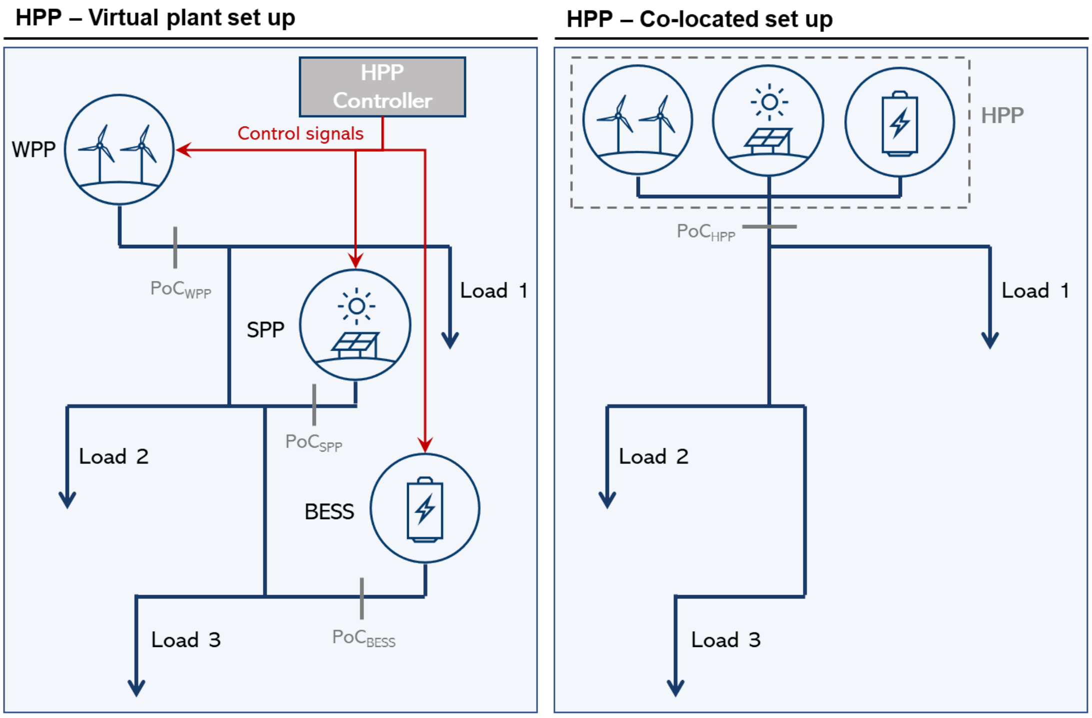

Figure 1.3: Co-located vs virtually connected HPP. Own preparation.

However, HPPs present not only benefits in front of stand-alone power plants, but also disadvantages, of which the most important are listed below based on [11].

- **Suboptimal siting.** The best site to harvest one type of resource does not necessarily match the best site to harvest another, so trying to find a place where both resources are negatively correlated may lead to the selection of suboptimal locations.
- **Financial/legal uncertainty.** Since most Grid Codes and relevant legislation do not include special terms for HPPs yet, specific requirements and benefits to HPPs can be more complex to achieve than those of individual technologies. In many cases, the requirements to HPPs are the same that those applied to the technologies combined [17].
- **Reduced battery's ability to provide maximum value.** If placed together with other assets, the HPP owners may want to restrict the usage of the batteries to maximize their own benefits, which may not be aligned with the needs of the power system. Therefore, there may be a suboptimal use of the batteries from the

whole grid's perspective[3].

- **Technical complexity.** Combining different technologies increases the difficulty in optimizing the sizing and operation of HPPs. Particularly, the various control systems of the plant become more complex and need a special attention. Herein lies the main focus of this study (as justified below).

Contemplating all the considerations above, it seems reasonable that a greater demand for HPPs appears, at least in regions with weaker grids. Some good examples of this are India and Australia, where the Grid Codes have pretty demanding requirements for power plants, thus enhancing the advantages of HPPs versus stand-alone technologies. Another critical advantage for weak power grids is the better utilization of the grid infrastructure and the consequent deferral of investments in transmission and distribution systems. Perhaps this last reason motivated the publication of hybrid-specific policy schemes in India [11]. On the other hand, regions with high differences in power prices within the same day, such as California, are witnessing a large amount of hybrid projects in development and construction phases [16]. This should in principle flatten the so-called "duck-curve"[4], motivated by high renewable penetration in the state of California.

Nevertheless, as explained above, there are still challenges to be faced by HPP developers and owners. Particularly, in the field of modelling and control of the plant, there has been extensive effort to develop advanced control systems for frequency support (these will be referenced in the Literature Review), but little to none attention has been placed in voltage and reactive power controllability. Thus, this study will humbly contribute to lay the groundwork of coordinated voltage control of HPP.

1.1.3 Challenges in voltage control and reactive power management

Unlike in the case of frequency - active power control loop, the voltage - reactive power control loop has a *local* character which is of great relevance. When there is an imbalance in a power system's frequency with respect to its nominal value, all generators within the synchronous system can contribute to restore the frequency by adjusting their active power generation accordingly. If the frequency is below its nominal value the generators will increase active power output, and they would reduce it in the opposite case[5].

However, this is not the case when there is a deviation of voltage with respect to its nominal value, since only nearby generators and reactive power sources will respond to

[3] Although this risk could be mitigated if appropriate requirements and rules are specified in the relevant Grid Codes.

[4] This refers to the residual load curve in regions with high renewable penetration (particularly solar energy). When subtracting VRE generation from total demand along a day's load curve, the resulting curve has a "duck shape", given by high demand in the evening which contrasts with low/zero generation from solar assets

[5] This is a simplification of how power flows and frequency control are managed in reality. In real life operation, TSOs need to consider specific aspects of the grid topology and state, such as the loading of transmission lines. Besides, delivering active power from long distances increases the power losses in the grid.

the imbalance. There are at least two fundamental reasons why voltage imbalances are handled using local resources. First, when the loading of a transmission line increases, its own reactive power consumption increases as well. So if reactive power is sent from a remote power plant, an important part of it will be consumed by the lines connecting the plant with the receiving bus. It is therefore preferable to have reactive power devices (such as shunt capacitors or shunt reactors) distributed among the grid to manage reactive power flows on a local basis.

Second, the interaction between reactive power flow and voltage in a bus imposes another constraint to the delivery of reactive power from a remote power plant. When there is a voltage drop in a particular bus, all nearby buses will experiment a certain voltage drop too, until the reactive power generated on-site increases and brings all voltages back to their nominal values. However, if trying to supply this missing reactive power from a far bus, all the buses in between will experiment an increase in their voltage level. This is generally not an issue if the voltages in the buses are below 1 pu but it can be problematic for buses in the way which have normal voltage values.

This problem is exemplified in Figure 1.4, where bus L3 has a low voltage which needs to be brought back to 1 pu by injecting reactive power. The initial situation (left) depicts voltage levels across the grid with no voltage control, the second image depicts an hypothetical situation if the remote generator supplies a large amount of reactive power to increase the voltage in bus L3, and the last image (right) shows another hypothetical situation where the reactive power is supplied within the own bus L3. The voltage levels profile in the third situation is ideal, while injecting reactive power from a long distance generates over-voltages in some buses in the way.

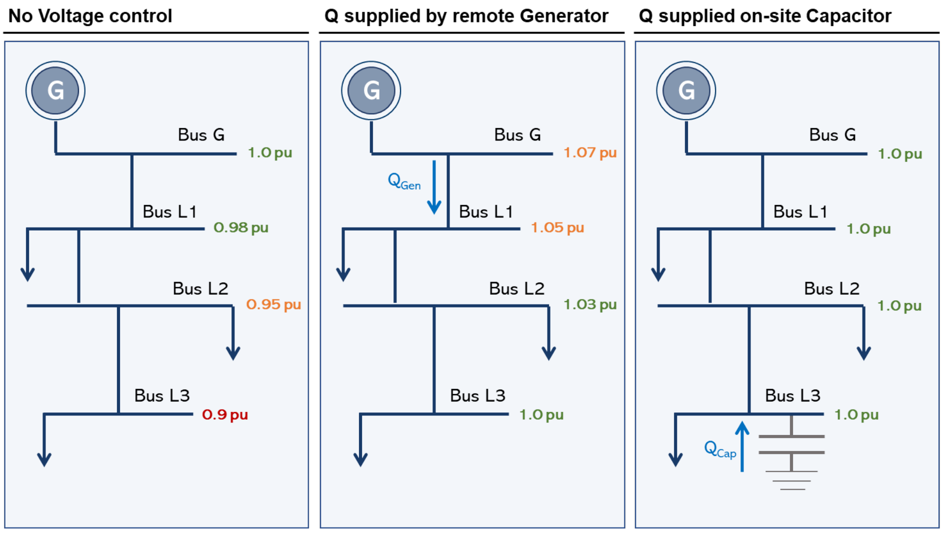

Figure 1.4: Voltage profiles in a grid with reactive power supplied from remote generator vs from on-site capacitor bank. Own preparation.

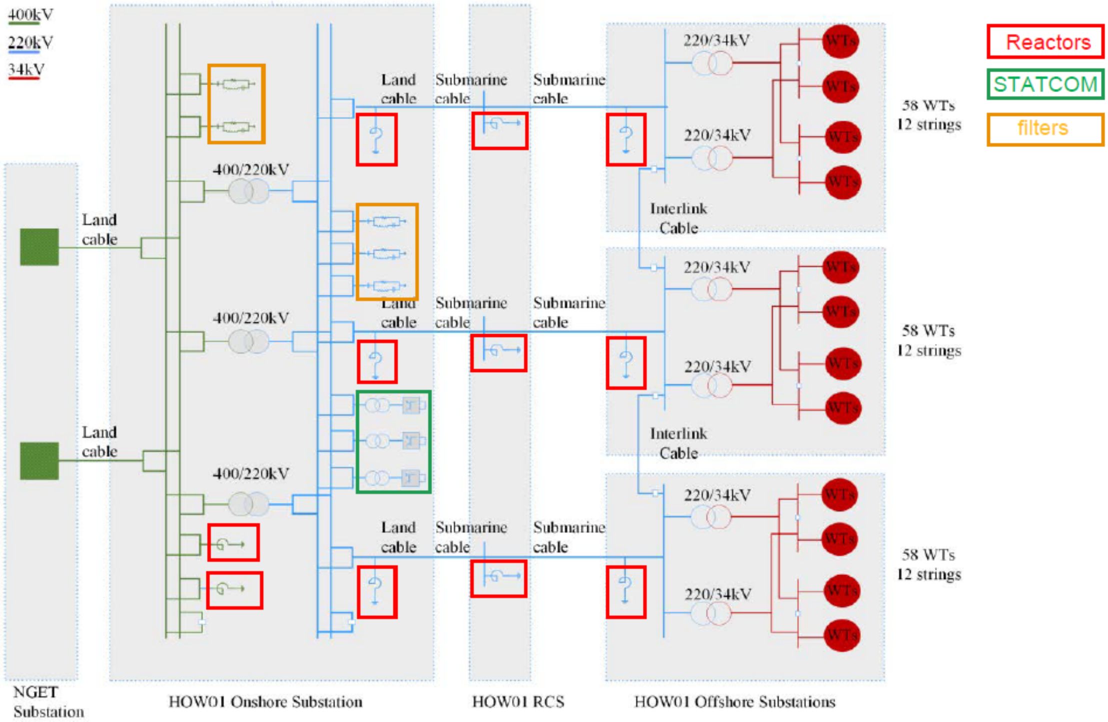

Figure 1.5: Single line diagram of Hornsea One Offshore WPP and export system. Adapted from [18].

This problem is well-known, and many authors have published different methodologies to address the issue by using an optimal reactive power dispatch algorithm, as explained in [19, 20, 21]. These papers address the management of reactive power flows from a transmission or distribution line operator view. On the other hand, extensive research has been dedicated to find the optimal location for reactive power resources such as Static Synchronous Compensators (STATCOMs) in the grid [22, 23].

However, the optimal location of reactive power sinks and sources is also of great relevance to plant owners and operators. As depicted in [18], several reactors, STATCOMs and other devices might need to be installed in the plant to enhance voltage stability and reactive power capability. Figure 1.5 exemplifies this complexity. It represents the electric diagram of Hornsea One offshore wind park, which is located off the Yorkshire coast.

The optimal placement of support devices such as STATCOMs or shunt capacitors can enhance the reactive power capability of a plant while minimizing the CAPEX. On the other hand, power plants with upgraded reactive power capability may have a better market value in front of other assets if new market products are designed for voltage control services, as the UK's TSO National Grid suggests in [24].

In this context, the optimal location of a STATCOM in the HPP will be also a matter of study in the project, as it is commented in Chapter 3.

The interaction of reactive power and voltage is addressed in Section 2.1 while the reasons to control voltage and reactive power flows are explained in Section 2.2.

1.2 Objectives and Scope of the project

This work studies the interaction and coordination of the different assets in a co-located HPP to produce a combined response against voltage deviations in the power system, through the management of reactive power exchange with the grid. The competence of the HPP in providing such service will be tested by comparison with the Danish Grid codes, as described in [25].

To achieve such a coordinated response, a novel control architecture needs to be developed, to account for each plant's reactive power capability and distribute power set-points accordingly. Furthermore, the addition of ancillary devices to support voltage control, such as STATCOM and transformers equipped with On-Load Tap Changers (OLTC) will be analyzed and included in the control architecture. The sizing of the STATCOM will be based on achieving enough reactive power capability to meet the Danish Grid Codes.

Lastly, the impact of different degrees of ownership of the grid on the HPP's reactive power capability will be studied too. In principle, owning part of the export lines reduces the capability of the plant, as more reactances and resistances are to be considered, but this also opens the door to installing a STATCOM closer to the Point of Common Coupling (PCC), which should enhance voltage controllability over such bus.

The objectives of the project can be summarized as follows:

- To develop a novel reactive power control architecture to produce a coordinated response against voltage imbalances in the grid. The architecture should be suitable to work in two different control modes: Specific Reactive Power Control and Voltage Control.
- To study the interaction of the different assets in the HPP, from the point of view of voltage control and reactive power management. The list of assets of interest includes a) Wind Power Plant, b) Solar Power Plant, c) Battery Energy Storage System, d) Static Synchronous Compensator and e) On-Load Tap Changer Transformer.
- To assess the aptitude of the HPP as a voltage control service provider, using the Danish Grid Codes as reference.
- To study how the addition of ancillary devices enhances reactive power and voltage controllability in an HPP.
- To evaluate how much additional reactive power capacity is needed to meet the Danish Grid Codes (if any).

- To analyze the impact of the ownership of the line and the location of reactive power sources on the plant's capability.

1.3 Contribution of this study

The main contributions of this project are listed below:

- **State of the Art of HPP.** A brief summary of the concept, advantages and challenges of HPP is provided already in this introduction, in Subsections 1.1.1 and 1.1.2.
- **Background of Q-V Interaction.** Section 2.1 provides a comprehensive theoretical background to understand the interaction between reactive power and voltage, which is harder to understand than the interaction between active power and frequency. The reasons for the need to control voltage and reactive power flows are also provided in 2.2.
- **Reactive Power Capability.** Section 2.3 explains how to obtain the reactive power capability curve of converter-based technologies, such as Type 4 Wind Turbines or solar PV inverters.
- **Modelling of HPP.** Section 2.5 provides an overview of the State of the Art of HPP modelling and control, with various references to other studies that focus on this topic.
- **Analysis of Grid Code Requirements**. Section 2.6.3 interprets the specifications of the Danish Grid Codes regarding voltage control and reactive power for power plants.
- **Novel control architecture for V and Q control in HPPs.** The core of this project is the development and verification of a control system that makes use of all the assets in an HPP to produce a coordinated response in front of voltage imbalances in the grid. The model for the HPP and the control architecture is developed in MATLAB/Simulink.
  - The control architecture covers the Asset, Plant and HPP control levels.
  - Two control functions are implemented: Specific Reactive Power control and Voltage control.
  - An external grid is modelled and integrated with the HPP model.
  - Different degrees of ownership of the HPP transformer and export line are studied by using 3 different scenarios.
  - A simple methodology to size the capacity of a STATCOM is implemented by comparison with the Danish Grid Codes. The methodology uses the dynamic model developed.

1.4 Assumptions and Limitations

The assumptions considered in the development of the study and their limitations are presented as follows:

- The reactive power capability of wind turbines Type 4, solar PV inverters, electrical batteries and STATCOMs can be obtained in a similar way, by using a voltage limitation constraint and a current limitation constraint. This is because all these technologies are based in power converters, whose capacity and limitations define the reactive power capability of the specific device.
- For simplicity, all wind turbines are assumed to produce the same amount of active and reactive power, and the same applies to all the solar PV panels. This neglects the spatial variations of wind speed and solar irradiation, as well as other significant differences (shadows, wake effect, etc.).
- The variability and uncertainty of wind speed and solar irradiance are neglected in this study. The simulations are conducted for short periods of time (up to few seconds), so that wind speed and solar irradiance are considered constant. In real operation, it is well known that oscillations in these natural resources can be captured by the wind turbines and solar PV panels, disrupting the active power generation and, therefore, the room for reactive power exchange with the grid (in other words, the reactive power capability).
- In the absence of specific Technical Regulations with requirements for HPP within the Grid Codes, the reactive power capability of the HPP is compared against the Danish Technical Regulations for Power Park Modules (PPM). More specifically, the Technical Regulation for Electrical Energy Storage Facilities, as specified in [26] is used as reference. This is done because *"storage plants have the same functional requirements as power park modules, so the requirements are principally the same [for all the technologies involved in the plant]"*[6].

1.5 Thesis Structure

The remaining part of this report is organized as indicated below:

- Chapter 2 presents the literature review. It provides the necessary theoretical background to understand the interaction between reactive power and voltage control and the need for controlling both. It also presents a methodology to calculate reactive power capability of selected technologies and the State of the Art of HPP modelling and control.
- Chapter 3 elaborates on the approach used for the modelling and control of the HPP. All the asset and plant models are explained together with the control architecture. The 3 scenarios used are also explained here highlighting the modelling and control differences from one to another.

[6] M. Andersen (Energinet), personal communication (e-mail), June 20, 2022.

- Chapter 4 presents all the results, sensitivity analysis and discussion
- Finally, Chapter 5 concludes and proposes ideas for future related works

2 Literature Review

2.1 Q-V interaction

This section is entirely based on Chapters 3.2 and 3.3 of [27] and the Appendix of [28]. The aim is to explain in a brief, conceptual way the interaction between reactive power and voltage, with a focus on inductors, capacitors and synchronous generators.

In Alternating Current (AC) systems, Reactive power (Q) is the component of complex power that oscillates back and forth through the lines and is exchanged between electric and magnetic fields, not getting dissipated. It is measured in Volt-Ampere Reactive (VAr). The need for managing reactive power is explained in Section 2.2. Active power (P) is the term used to refer to the "useful" energy that a generator is producing, or a load is consuming. It is the part of the total power that is effectively transformed into another type of energy, such as calorific or mechanical energy. It is measured in Watts (W). Finally, the vector summation of these two gives the apparent power (S), so the module of S can be obtained as follows:

$$S = \sqrt{P^2 + Q^2} \tag{2.1}$$

Power Factor (PF) is a measure of the amount of "useful" energy that a generator is delivering, or a load is consuming. It expresses how much active power is being produced or consumed, as compared with total apparent power. It is linked to the phase difference between current and voltage (ϕ). The large phase difference there is between voltage and current, the more reactive power is being exchanged, and the less active power is being transmitted with respect to apparent power:

$$PF = \frac{P}{S} = cos(\phi) \tag{2.2}$$

2.1.1 Inductors and Capacitors

Inductors

The behavior of an inductor or solenoid is linked to the magnetic field induced by any electric current flowing through it. When placed in an AC circuit, this magnetic field varies with time in a similar way that the current flowing through the cable, i.e., sinusoidally. At the same time, this variable magnetic field induces a second current in the inductor which opposes to the main current, and whose value depends on the rate of change of the magnetic flux[1]. In other words, the inductor shows an inhibiting effect on a change in the current flow which results in a delay or phase shift of the current with

[1] As per Faraday's Law of Induction, mathematically expressed as: $\epsilon = -d\theta/dt$ where ϵ is the electromotive force and θ is the magnetic flux

respect to voltage. An ideal inductor produces a delay of the current with respect to voltage of 90°. This is commonly referred as a *lagging* current. Lagging and leading currents are represented in Figure 2.1 together with voltage, in both temporal[2] and phasor representations.

Figure 2.1: Leading and Lagging current vs Voltage. Own elaboration.

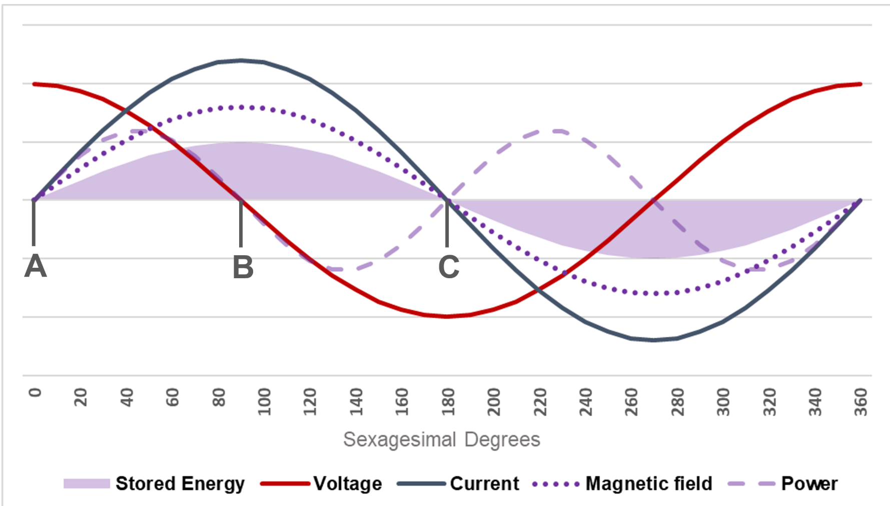

Figure 2.2: Voltage, current, magnetic field and stored energy in an inductor. Adapted from [28].

[2]Considering a frequency of 50 Hz

Another way to look at this is by understanding that an inductor is actually storing and releasing energy continuously on its magnetic field. Figure 2.2 illustrates this idea by representing the voltage, current, magnetic field, power and energy stored in an ideal inductor connected to a voltage source. When the voltage is at its maximum, current starts to build in the inductor (point A) and stores energy in the magnetic field. When voltage reverses (Point B), the current is still flowing to the inductor because of the energy stored in the magnetic field, which is weakened as it releases it. Lastly, in Point C, current, magnetic field and energy stored become zero, and the current and magnetic field start building in the opposite direction driven by the negative voltage.

Capacitors

A capacitor consists of two conducting surfaces facing each other and separated by a small gap. The plates can carry an electric charge, which generates an electric field in the capacitor. A capacitor stores and releases energy by means of its electric field in a similar way that inductors do in their magnetic field. It is commonly said that AC "can get across the capacitor". The impulses that electrons transmit to each other get through the gap thanks to this electric field (provided the voltage keeps changing), so current can flow through the gap in AC.

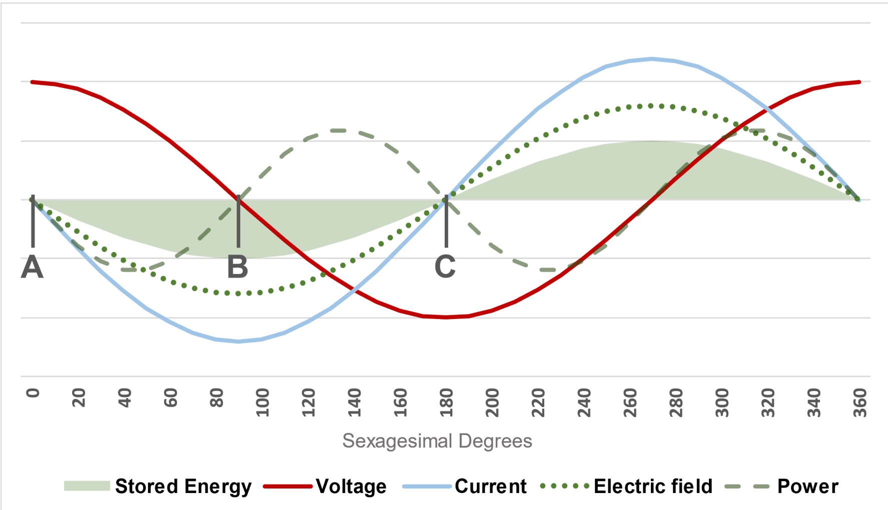

Figure 2.3: Voltage, current, electric field and stored energy in a capacitor. Own elaboration based on [28]

The value of the current flow is proportional to the rate of change of the electric field (and, therefore, to the rate of change of voltage). An ideal capacitor connected to a voltage source makes the current *lead* voltage, and the energy is stored and released just like in an inductor, but at opposite intervals. This can be observed by looking at Figures 2.2 and 2.3. Both share the voltage source (red line), but the current, power, electric/magnetic fields and stored energy are shifted. It is easy to appreciate that power flows from the voltage source to the inductor in the interval A to B, and then gets back to the voltage source from B to C. In the capacitor, power flows to the voltage source in the interval A to B, and gets back to the capacitor from B to C. This fashion repeats for the rest of the cycle in both cases.

Voltage Drop
Overall, both elements have a very similar behavior in the presence of an AC voltage source, but it is shifted in time. When one of them is storing energy, the other one is releasing it. This is extremely useful, because it allows to use one of them to cancel the other, as explained in Section 2.2. By convention, inductors are often referred to as reactive power sinks and capacitors are referred to as reactive power sources (even if there is no net ”consumption” or ”production” of reactive power).

Voltage drop results from the interaction of the current being transmitted through impedances in the lines (resistances, inductances and capacitances). It is expressed by Equation 2.3, where:

- X_L is the line's inductive reactance
- X_C is the line's capacitive reactance
- R is the line's resistance
- $\mathbf{V_{drop}}$ is the voltage drop across the line
- $\mathbf{I}$ is the current flowing through the line, expressed in phasor quantity

$$\mathbf{V_{drop}} = \mathbf{I} * (R + j(X_L - X_C)) \tag{2.3}$$

To understand the impact of reactances and capacitors on voltage drop, Figure 2.4 illustrates the phasor diagrams of the voltage at the beginning (U_A) and end of the line (U_B) together with current supplied to the load (I_{load}), and the voltage drops in a purely inductive line ($U_{L,line}$) and purely capacitive line ($U_{C,line}$).

If taking U_B as the reference voltage and placing a certain I_{load}, the voltage drop over the line can be drawn as a phasor that is perpendicular to the current and begins at the end of the phasor U_B. Its module would depend on the line impedance and the current value (as described in Equation 2.3). The figure shows how, for an inductive load, the voltage drop is larger with an inductive line, while the capacitive line can even have a negative voltage drop. This means that the voltage at the end of the is higher than at the beginning, and is depicted on the right hand side of the figure.

Generally speaking, power systems have an inductive character since most of the devices in the grid (generators, transformers, overhead lines, motors...) contain or behave as inductors, so capacitor banks are often used to compensate this inductive behavior, bring the PF closer to 1 and reduce voltage drop. With landed cables, though, a capacitive effect is more common due to the proximity of cables and ground, so reactances may be needed to avoid overvoltages.

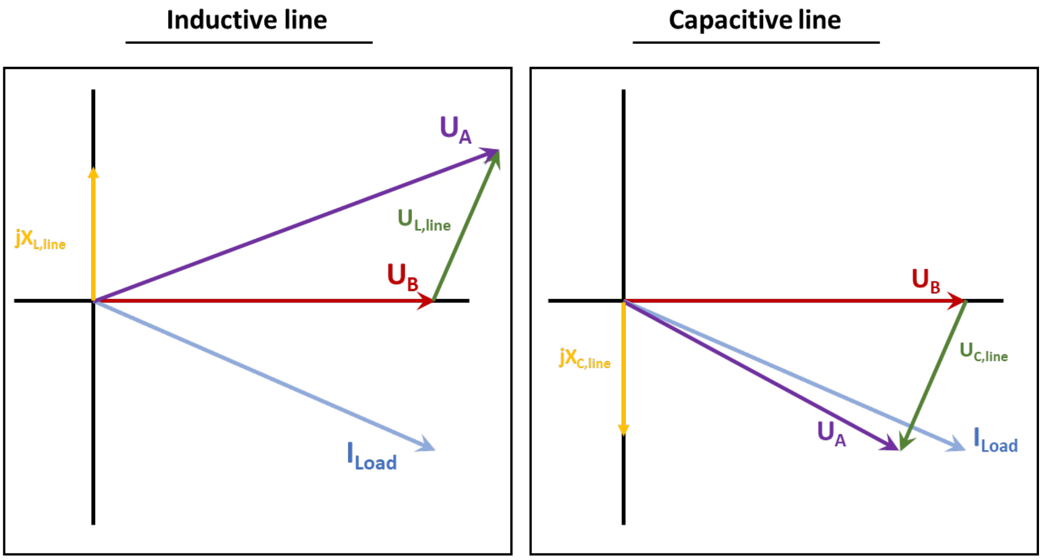

Figure 2.4: Voltage drop across an inductive (left) and capacitive (right) line, given an inductive load. Own elaboration.

2.1.2 Synchronous Generators

This section is based on Chapter 4.3 of [27].

The relation between reactive power produced by generators and voltage is not as intuitive as the relation between active power and frequency. A first appreciation is that, by increasing the Direct Current (DC) in the rotor (excitation current), there is an immediate increase in the magnetic field in the rotor, and this in turn increases the voltage in the stator. In other words, by modifying the excitation current in the rotor, the voltage at the generator's terminals is rapidly changed.

The voltage phasor in the stator is always lagging 90° with respect to the magnetic flux phasor, while the position of the current phasor will depend on the nature of the load.

- If the current is in phase with the stator voltage, the load is resistive and the PF is 1, so the generator does not supply or absorb reactive power.
- If the current is lagging the stator voltage, the load is inductive and the generator needs to supply (act as a capacitor) reactive power. This is the common situation, as loads tend to be inductive.
- If the current is leading the stator voltage, the load is capacitive and the generator needs to absorb (act as a inductor) reactive power.

This situation can also be represented through the magnetic fields of rotor and stator. Recall that a rotor in a synchronous machine is composed by a DC current that produces a static magnetic field, which spins at the rotor speed. On the other hand, the three phases in the stator generate a spinning magnetic field with a constant value, which spins at the grid's frequency. In synchronism, both fields spin at the same time, but they show a certain phase shift, which describes the behavior of the generator. The "more perpendicular" these field are, the more torque is exchanged. In the extreme case, if these fields are parallel, there is no transmission of torque between rotor and stator.

For analytic purposes, the stator field is sometimes represented as the sum of two separate phenomena: one component is parallel to the rotor field and another is perpendicular. The latter represents the transmission of torque between rotor and stator; the former expresses and addition (leading power factor) or subtraction (lagging power factor) to the stator field. This is represented in Figure 2.5.

When the power factor lags, the stator field weakens the rotor field and, therefore, the voltage in the stator is reduced. This situation is considered a delivery of reactive power from the generator. On the opposite case, when the power factor leads, the stator field enhances the rotor field and, likewise, the voltage in the stator.

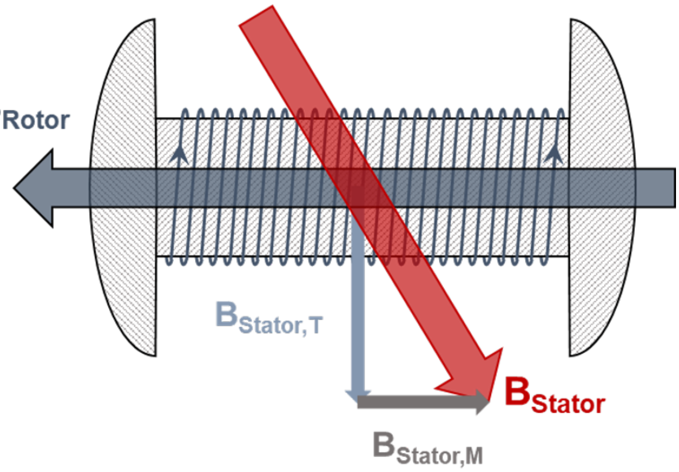

Figure 2.5: Magnetic field of rotor and stator in a synchronous generator supplying power to an inductive load. Own elaboration based on [27].

2.2 Why should voltage and reactive power be controlled?

This section justifies the need for controlling voltage levels and reactive power flows throughout the power grid. It is based on Chapter 1 of [28].

On AC power systems, voltage is mainly controlled through the management of reactive power production and absorption. There are three main reasons why voltage and reactive power need to be monitored and controlled:

1. Both consumers and generators are equipped with electrical and electronic devices which are designed to work within certain voltage levels (typically with a margin of ±5% from the nominal value). If such devices work outside these limits, they may

perform poorly. For instance, at low voltages bulbs provide less illumination and electric motors demand higher current and can overheat and get damaged. With too high voltages, the insulation of cables and other elements may be destroyed, causing short circuits and potentially breaking the devices.

2. The presence of reactive power flowing through the grid is associated with additional current, which incurs costs in the form of additional active power losses due to Joule effect. Therefore, an optimal management of reactive power flow can minimize these losses.

3. The fact that generators need to supply reactive power increases the capacity requirements in both generators and lines[3]. An optimal strategy of reactive power management can also prevent unnecessary investments in generator's capacity.

Two additional considerations are worth mentioning here. First, the transmission and distribution lines act themselves as reactive power sources or sinks, depending on the load they are carrying. With very light loads (below the so-called Surge Impedance Load [SIL]) the lines behave as a capacitor, thus delivering reactive power. On the other hand, when carrying high loads (above SIL) the lines behave as an inductor, thus absorbing reactive power.

Second, similarly to the frequency-active power loop (P/f) of a power system, where all generators increase or decrease their active power generation after there is a frequency event in the grid, in the voltage-reactive power loop (Q/V) all generators (and other components) *in a particular zone* act to amend an imbalance of reactive power. This prevents the voltage in some buses from collapsing when there has been an important event (e.g., the loss of a large generator).

Nonetheless, P/f and Q/V loops also have dissimilarities which need to be considered. Two critical differences to bare in mind are as follows:

- Frequency is a "global" variable, meaning that following an event in any point of the grid (for instance, a sudden load increase) frequency will change in all the system, and the power loss shall be also compensated from any point of the grid. However, voltage is a "local" variable, meaning that when there is a voltage drop in a particular bus of the system, only nearby generators can solve the problem by injecting more reactive power.

- The generation of real power requires the conversion from other energy source, which can be chemical, mechanical, calorific, etc. However, the absorption/generation of reactive power does not need for any kind of "fuel" to be consumed. As a matter of example, a PV inverter will only produce active power if the solar modules attached are being hit by solar irradiation, but this is irrelevant for the reactive power it consumes/delivers.

[3]As it is explained in Section 2.3, the delivery/absorption of reactive power by generators diminishes the room for active power generation

2.3 Reactive power capability of converter-based power plants

Electrical machines have certain limitations with respect to the current and voltage they can stand. This imposes constraints on the active and reactive power exchanged between generator and grid to preserve its integrity under normal operating conditions. If these constraints were not respected, the machine would be subjected to overloading or overvoltage, which can destroy the insulating material on the generator and lead to a short circuit [27].

The reactive power capability curve of a generator represents how much reactive power it can exchange with the grid depending on the active power that it is producing. This is commonly depicted as a closed area in a P-Q plot, where P is represented in the x-axis and Q in the y-axis. This area is typically the result of the interaction of several curves, each of which symbolizes a particular constraint of the machine.

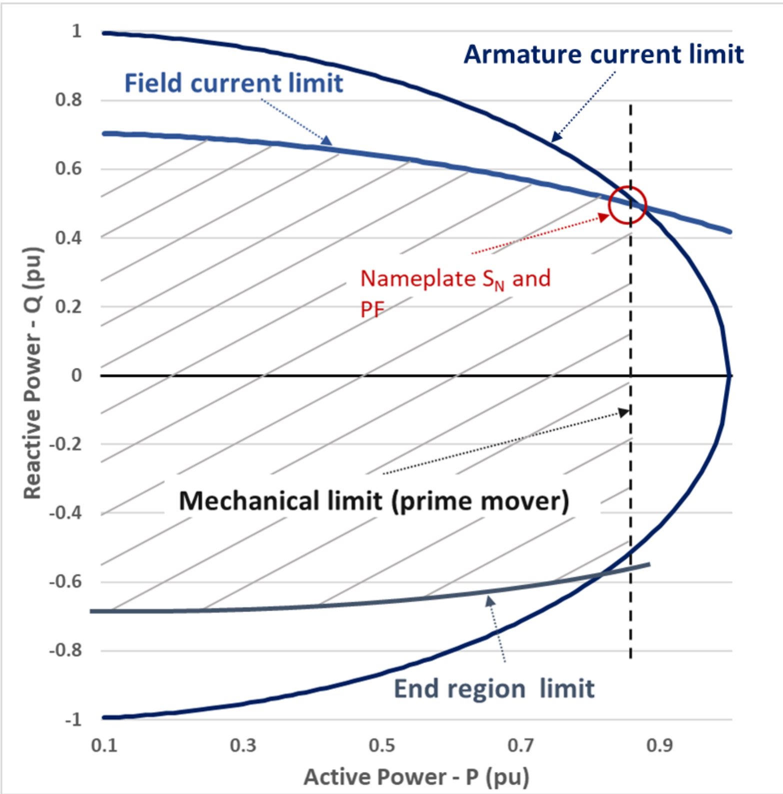

Figure 2.6: Reactive power capability curve of a synchronous generator. Own preparation based on [29] and [30]

The constraints are technology-dependent, so a PV inverter and a synchronous generator have different capability curves. As a matter of example, a traditional synchronous machine[4] has three main constraints: armature (stator) current limit, field (rotor) current limit and end region limit. An example of capability curve for a synchronous machine is depicted in Figure 2.6, [29] and [30].

Fortunately, the reactive power capability of converter-based technologies, such as wind turbines, PV inverters and batteries is very similar, since the limitations come from the maximum value of current and voltage that the power converters can stand before experiencing overload/overvoltage. This idea is depicted in [31] in the form of reactive power capability curves and it is supported by [32] and [33], which use a similar methodology to characterize the reactive power capability of wind turbines Type 4 and PV inverters, respectively. Therefore, this chapter will derive the reactive power capability of a wind turbine and a complete WPP, to then generalize the process for the SPP and BESS.

2.3.1 Reactive power capability of wind turbine and WPP

This section is based on [32]. Figure 2.7 depicts a diagram of a wind turbine Type 4 and its connection with the rest of the WPP through the collection system. According to [34], wind turbines Type 4 include a pair of back-to-back converters that fully decouple the generator from the grid's frequency, allowing for variable rotational speed in the turbine, while P and Q can be controlled separately. Normally, the Machine-Side Converter (MSC) controls P and the AC voltage at the generator terminals, while the Grid-Side Converter (GSC) controls Q and the voltage at the DC link between both converters.

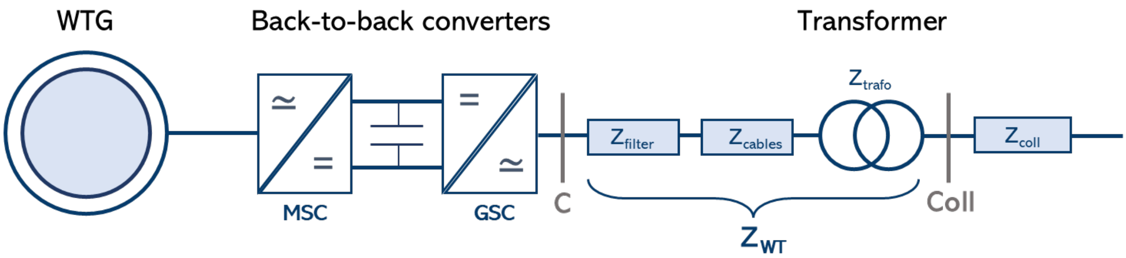

Figure 2.7: Diagram of a Wind Turbine Generator (WTG) connected to a WPP's collection system. Own preparation.

The GSC is connected to a transformer to raise the voltage level (typically from 690 V to 11/33 kV) through a short cable and a filter with certain impedances. The transformer is then connected to the collection system of the WPP, where the power coming from all the turbines is gathered and sent to the grid. In the figure, Z_{filter} represents the impedances of the filter and Z_{cables} the impedance of the cables connecting the GSC with the transformer, whose impedance is Z_{trafo}. Lastly, Z_{coll} represents the impedance of all the cables and/or lines that connect the turbine with the collection system of the WPP.

Considering Figure 2.7, to assess the reactive power capability of a wind turbine at the

[4] Like the ones used in gas-fired or hydro power plants

high-voltage side of the transformer (point *Coll* in the diagram), all the impedances between the GSC (point C of "Converter", in the diagram) and the high-voltage side of the transformer need to be considered. In all the equations below, Z_{WT} represents the sum of Z_{filter}, Z_{line} and Z_{trafo}. There are two main limitations for the reactive power capability of a wind turbine Type 4, as well as other generators that rely on power converters. The equations describing both limitations are introduced below.

Voltage limitation

The active and reactive power flowing to the collection system (measured at the high-voltage side of the transformer) can be expressed as follows (letters in bold indicate a phasor quantity):

$$P_{coll} + jQ_{coll} = \mathbf{V_{coll}} * \mathbf{I^*_{coll}} \tag{2.4}$$

The current flowing to the collection system is:

$$\mathbf{I_{coll}} = \frac{\mathbf{V_{coll}} - \mathbf{V_C}}{Z_{WT}} \tag{2.5}$$

Equation 2.6 is obtained by replacing $\mathbf{I_{coll}}$ in Equation 2.4 with the right-hand side of Equation 2.5.

$$P_{coll} + jQ_{coll} = \mathbf{V_{coll}} \left(\frac{\mathbf{V_{coll}} - \mathbf{V_C}}{Z_{WT}} \right)^* \tag{2.6}$$

After separating in real and imaginary parts and performing several mathematical manipulations and rearrangements (for full mathematical demonstration see [32]), the constraint for reactive power of a wind turbine based on converter voltage limitation is given in Equation 2.7 below. Notice that after the mathematical rearrangements no phasors are present in the equation anymore, but only scalar quantities which are typically expressed in pu:

$$Q_V = \sqrt{\left(\frac{V_{coll} V_C}{\sqrt{R^2_{WT} + X^2_{WT}}} \right)^2 - \left(P + \frac{V^2_{coll} R_{WT}}{R^2_{WT} X^2_{WT}} \right)^2} - \frac{V^2_{coll} X_{WT}}{R^2_{WT} + X^2_{WT}} \tag{2.7}$$

This Equation provides the voltage limitations for the injection ($Q_{V,inj}$) and absorption ($Q_{V,abs}$) of reactive power when V_C is replaced by the maximum ($V_{C,max}$) and minimum ($V_{C,min}$) allowable converter voltages, respectively.

It must be noticed here that, for a certain $V_{C,max}$, the maximum value of Q that can be exported is limited by the value of V_{coll}. This can be observed in Equation 2.7 since V^2_{coll} is subtracting both from inside and outside of the square root. So, the larger V_{coll}, the less Q can be injected by the wind turbine.

Equation 2.8 provides a better picture of this idea[5]. This equation calculates the amount of reactive power exchanged between two buses separated by a purely inductive line, where U_S is the voltage of the *Sending* bus and U_R is the voltage of the *Receiving* bus. Considering that $cos(\delta) \leq 1$, the flow of reactive power from bus S to bus R will happen only if U_S is larger than U_R. Following this reasoning, the Q absorption capability for a given $V_{C,min}$ is also limited with low values of V_{coll}.

$$Q_{S \to R} = \frac{U_S * U_R * cos(\delta) - U_R^2}{X_{line}} \tag{2.8}$$

Current limitation
The rated apparent power at the high-voltage side of the generator is given by 2.9, where I_{Cmax} represents the maximum allowable current of the GSC.

$$P^2 + Q^2 = S^2 = (V_{coll} I_{Cmax})^2 \tag{2.9}$$

This can be rearranged to obtain the current limitation for the injection and absorption of Q:

$$Q_I = \pm\sqrt{(V_{coll} I_{Cmax})^2 - P^2} \tag{2.10}$$

The positive root provides the current limitation for the injection of reactive power ($Q_{I,inj}$) while the negative root provides the limitation for the absorption of reactive power ($Q_{I,abs}$).

Reactive power capability of wind turbine Type 4
Finally, the capability of reactive power injection and absorption of a wind turbine Type 4 given a certain level of P is provided by the minimum and maximum values of the correspondent voltage and current limitations (respectively), as expressed below:

$$Q_{inj,max,WT} = min(Q_{V,inj}, Q_{I,inj})$$
$$Q_{abs,max,WT} = max(Q_{V,abs}, Q_{I,abs})$$

It is important to note here that the reactive power capability could have been characterized at any point of the diagram, by using the correspondent voltage and all the impedances between the GSC and the point of choice.

Using data displayed in Table 2.1 in Equations 2.7 and 2.10, the reactive power capability curve of a wind turbine Type 4 can be easily obtained, as depicted in Figure 2.8. As indicated in the table, the curve corresponds to a voltage level in the collection system (V_{coll}) of $0.95pu$. For higher voltages the curves are moved down, so the injection capacity is reduced and the absorption capacity is increased.

[5]This Equation is not part of the Q capability of a wind turbine, but it can be applied to any two buses separated by an inductive line. The equation is presented just for clarification purposes.

Table 2.1: Parameters of the WT for Q capability calculation [32]

Parameter	**Value (pu)**
R_{WT}	0.0084
X_{WT}	0.135
V_{Cmax}	1.1
V_{Cmin}	0.8
V_{coll}	0.95
I_{Cmax}	1.25

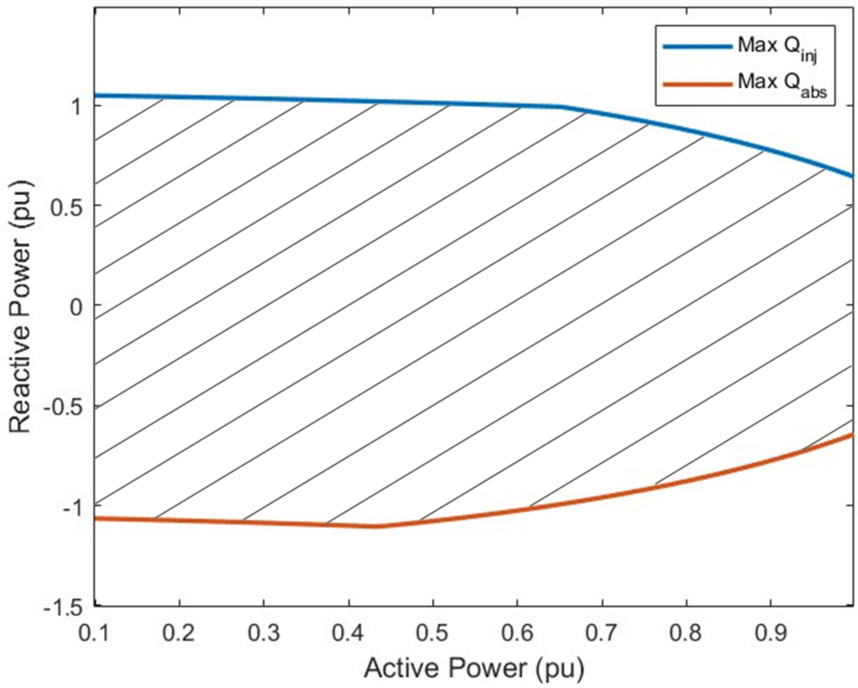

Figure 2.8: Reactive power capability of a WT Type 4. Own preparation based on [32]

Reactive power capability of WPP

Recall Figure 2.7. To calculate the reactive power capability of a wind turbine in the point *Coll* all the impedances between the GSC and that point had been considered. Now, to calculate the capability of a whole WPP, Equations 2.7 and 2.10 can be applied again, but using the new impedance Z_{WPP} which includes the resistance and reactance of the collection system. Z_{WPP} is the equivalent impedance of the whole collection system, and it can be calculated for every particular topology using the methodology proposed in [35].

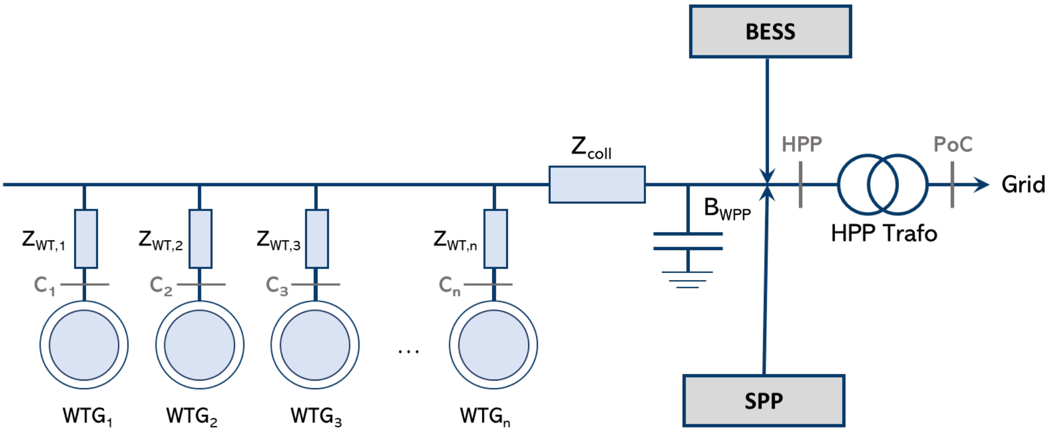

Figure 2.9: Generic diagram of a WPP connected to the main HPP transformer. Own preparation.

Table 2.2: Parameters of the WPP for Q capability calculation [32]

Parameter	Value (pu)
R_{WPP}	0.02
X_{WPP}	0.136
V_{Cmax}	1.1
V_{Cmin}	0.8
V_{HPP}	0.9
B_{WPP}	0.021
I_{Cmax}	1.25

Same as before, the capability of reactive power injection and absorption of the WPP is given by the minimum and maximum values of the correspondent voltage and current limitation (Equations 2.11 and 2.12 respectively), plus an additional term that accounts for the reactive power injection of the capacitive cables in the collection system:

$$Q_{V,WPP} = \sqrt{\left(\frac{V_{HPP}V_C}{\sqrt{R_{WPP}^2 + X_{WPP}^2}}\right)^2 - \left(P + \frac{V_{HPP}^2 R_{WPP}}{R_{WPP}^2 X_{WPP}^2}\right)^2} - \frac{V_{HPP}^2 X_{WPP}}{R_{WPP}^2 + X_{WPP}^2} \tag{2.11}$$

$$Q_{I,WPP} = \pm\sqrt{(V_{HPP}I_{Cmax})^2 - P^2} \tag{2.12}$$

$$
\begin{aligned}
Q_{inj,max,WPP} &= min(Q_{V,WPP,inj}, Q_{I,WPP,inj}) + B_{WPP}V_{HPP} \\
Q_{abs,max,WPP} &= max(Q_{V,WPP,abs}, Q_{I,WPP,abs}) + B_{WPP}V_{HPP}
\end{aligned}
$$

Using Equations 2.11 and 2.12 and data provided in Table 2.2 (taken from [32]), the reactive power capability of a WPP can be obtained, as depicted in Figure 2.10.

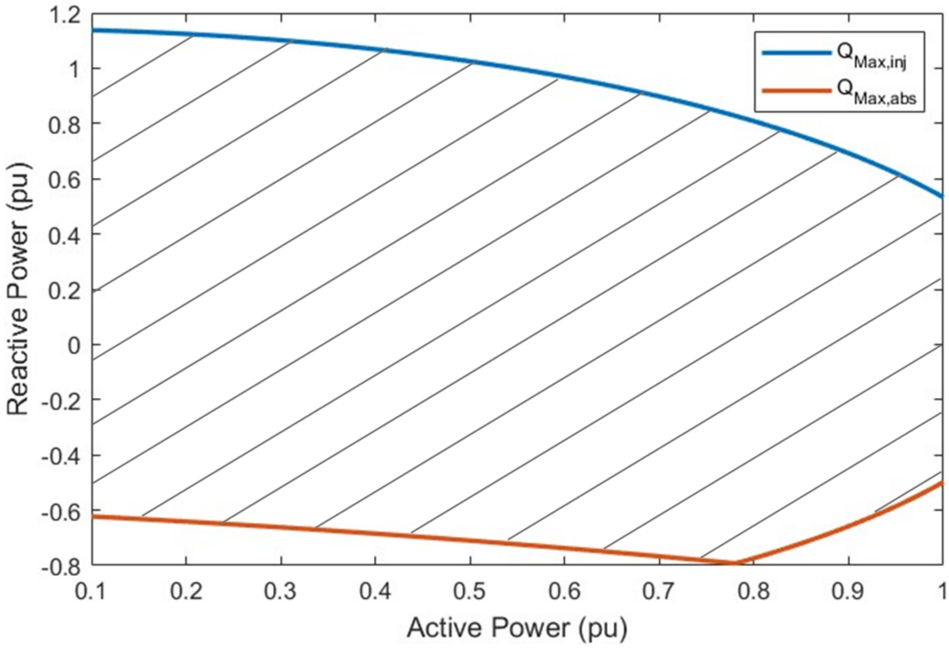

Figure 2.10: Reactive power capability of a WPP. Own preparation based on [32]

As it is depicted in [31], and aligned with [33] and [26], the reactive power capability of a PV inverter and a battery are obtained in a very similar way to that of a wind turbine Type 4, and the same applies to a whole SPP and BESS if compared with a WPP.

2.4 Reactive power capability of STATCOM

A Static Synchronous Compensator (STATCOM) is a reactive power support device typically used in power plants to enhance the Q capability of the plant, or in selected buses of a distribution or transmission system, to enable voltage controllability along the grid. It consists of a Voltage Source Converter (VSC) with a DC-link, a coupling reactance and a coupling transformer. Generally, there are two controllers in a STATCOM: one to control the reactive power exchange with the grid, and another to control the DC-link voltage [36]. Figure 2.11 illustrates the main components of a STATCOM.

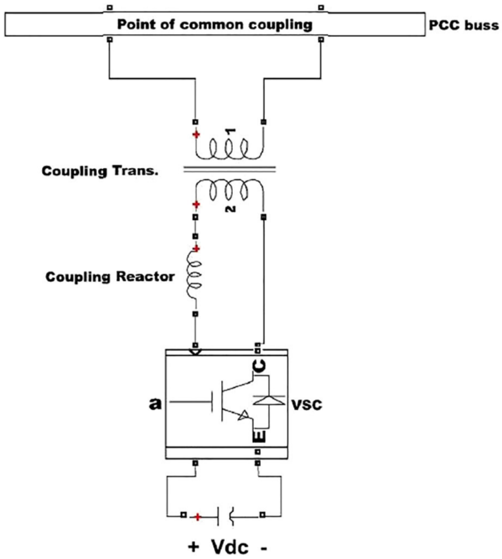

Figure 2.11: Overview of STATCOM's main components. [36]

The Q capability of the STATCOM is obtained in a similar way as in the WPP, SPP and BESS cases (since the STATCOM is also limited by its converter capabilities), however the STATCOM does not produce any P, so Equations 2.12 and 2.11 are simplified as follows:

$$Q_{V,STAT} = \frac{(V_C - V_{HV,STAT}) * V_{HV,STAT}}{X_{STAT}} \tag{2.13}$$

$$Q_{I,STAT} = \pm I_{C,max} * V_{HV,STAT} \tag{2.14}$$

These equations represent the voltage and current constraints given by the STATCOM's converter limits. The limits to the injection capability are obtained by replacing V_C with $V_{C,max}$ in Equation 2.13 and taking the positive value in Equation 2.14. The limits to the absorption capability are obtained by replacing V_C with $V_{C,min}$ in Equation 2.13 and taking the negative value in Equation 2.14.

So, the injection and absorption capability are expressed as follows:

$$Q_{inj,max,STAT} = min(Q_{V,inj}, Q_{I,inj})$$
$$Q_{abs,max,STAT} = max(Q_{V,abs}, Q_{I,abs})$$

2.5 Modelling and Control of Hybrid Power Plant

Following the development of the first HPPs, various researchers worldwide have produced dynamic models and control architectures to study the behavior of HPP and find out what the best strategies are to monitor and control them. Extensive effort has been dedicated to understand the roles of the diverse control levels involved in an HPP, and how they should interact with each other.

Once this overall control architecture was clear, significant studies have revolved around active power and frequency control. A hot topic within this area is to address the vulnerability of systems with low inertia caused by high renewable penetration using HPP with special control functions. Various studies have proposed different strategies to deliver Fast Frequency Response (FFR), an ancillary service specifically designed to compensate for low inertia[6] [37]. MATLAB/Simulink and DigSilent PowerFactory are the preferred simulation tools to validate the models, as referenced below.

Authors in [38] lay the foundations of HPP control by designing and implementing an HPP controller which distributes the external commands for curtailments to the different components of the plant through a dispatch function. This was firstly implemented in MATLAB/Simulink and deployed later in an existing power plant.

In [39] a hierarchical control strategy is implemented to regulate the overall active power injected into the grid. The study focus on the HPP controller, which receives reference signals from the Energy Management System (EMS) and dispatches active power setpoints among the diverse power plants. Two control modes are implemented: Maximum Power Point Tracking (MPPT) and power reference following. To validate the proposed strategies, a model is implemented in MATLAB/Simulink.

In [40] a control architecture is developed to coordinate the assets in a renewable-based HPP to provide frequency support services to the grid. In particular, the study focuses on FFR and Frequency Containment Reserve (FCR, also called Primary Frequency Reserve) and considers the latest regulations and recommendations by ENTSO-E[7]. The model is developed in MATLAB/Simulink and it is tested in a system with reduced inertia.

In the same line, authros in [41] and [42] present a dynamic model in DigSilent PowerFactory to enhance active power controllability in front of constant and turbulent weather conditions. The model is firstly validated under normal operation, and then its ability to provide ancillary services is assessed as well. Particularly, Frequency Regulation and Low-Voltage Ride Through are implemented.

[43] studies the performance of a Supercapacitor in a HPP to provide FFR. The results show that the Supercapacitor effectively reduces the Rate of Change of Frequency (Ro-

[6] Power systems with high renewable, converter-based penetration (such us wind turbines Type 3 and 4 or PV facilities) tend to have reduced inertia because the converters decouple the generator from the grid. Therefore, these systems are more sensible in front of frequency events like the sudden trip of a large generator.

[7] ENTSO-E stands for European Network of Transmission System Operators.

CoF) and increases the frequency nadir. Various locations of the Supercapacitor are tried to compare is performance under different conditions. The model is implemented in DigSilent PowerFactory.

Authors of [44] explore the interface between the EMS and HPP controller of the plant, defining the roles of each party and the variables exchanged between both. The aim is to better understand the impact of market-related functions on real time operation, as well as addressing how to keep the EMS updated for better optimization. This is crucial in renewable-based HPP, because weather forecasts become much more accurate as delivery time gets closer, so having the latest information available reduces forecast errors. Time coordination and robustness over communication failure are also explored and discussed in the paper.

The EMS is in charge of maximizing the revenue of the power plant through optimal market bidding and dispatch. On the other hand, the HPP controller executes the dispatch plans by distributing set-points among the portfolio.

[45] is a PhD project with several contributions to this research topic, among which the most relevant in this field are a) a procedure to develop plant models suitable for control design, tuning and verification; b) an energy management system designed to handle power variability and uncertainty; and c) a new methodology for designing and tuning the power management system.

Authors in [46] develop a novel control architecture with four control levels: asset control level, plant control level, HPP control level and HPP EMS level. This methodology has been a great source of inspiration for the reactive power control architecture developed in this project, so it is further summarized below.

2.5.1 Hierarchical Control Architecture of Hybrid Power Plants

This section is based on [46]. Hierarchical control architecture has been adopted in many stand-alone renewable power plants, with two control levels. Particularly, a plant control level watches power flows at the PoC and dispatches control commands to individual assets. On the other hand, asset control level makes sure that these commands are followed by each asset, which can be a single wind turbine or a group of solar PV panels connected to an inverter, for instance. In few words, overall active and reactive power references for the power plant are allocated to each individual asset based on its available power, and the asset controller tracks its own references. However, some specific features of the plant can be implemented at the asset level only. For example, FFR is normally implemented at the asset level because it requires very fast response, a requirement that may not be fulfilled if communication delays between asset and plant controller arise.

For HPP, the architecture is more complex because there are several power plants that must be coordinated towards the same targets. Up to 4 different control levels are defined in the hierarchical control architecture of an HPP.

- **HPP EMS**. The objective of the HPP EMS is to maximize the revenue of the power plant, while respecting utility regulations and the physical limits of the assets. To do so, the EMS optimizes the energy bids in the market considering the plant's availability and the latest forecast on energy generation. This is an iterative process where the bids are constantly updated in the diverse energy markets (Day-Ahead, Intraday and Balancing Markets) as the newest forecast is received by the EMS before the delivery time arrives.

- **HPP Controller**. The HPP Controller makes sure that the market commitments carried out by the HPP EMS are complied at all time. In other words, it watches that the energy delivered to the grid is the same (or as close as possible) as the energy sold in the market. Other functions of the HPP Controller include respecting the power limitations imposed by the network and ensuring that reactive power flow and voltage at the PoC follow the set-points given by the TSO.

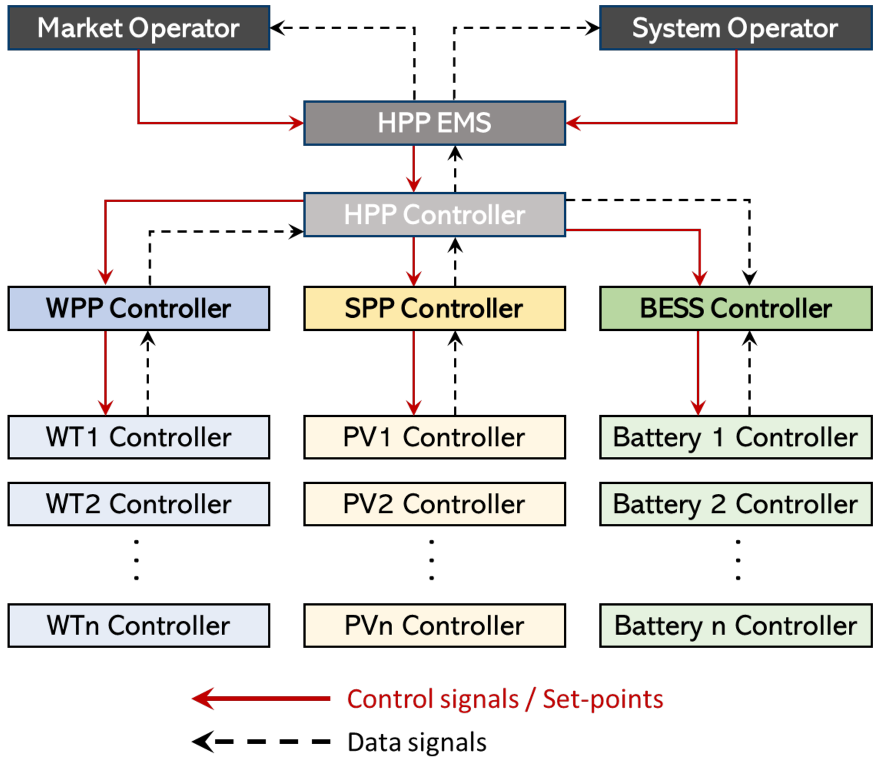

Figure 2.12: Diagram of a hierarchical control architecture in an HPP. Own preparation based on [46].

- **Plant Controller**. The Plant Controllers ensure that the power delivered by each individual plant follows the set-points provided by the HPP Controller. To do so, it distributes active and reactive power references for each asset based on the HPP Controller commands using a dispatch block. There are a number of approaches for the dispatch strategy, such as dispatching according to availability or based on an optimization algorithm. Additional control loops can be added to enable advanced control applications, such as frequency control, voltage control or Fault Ride-Through (FRT) coordination.

- **Asset Controller**. Asset Controllers guarantee that output voltage and current at the asset terminals follow the control commands received from the Plant Controller.

As depicted in Figure 2.12, overall control signals and set-points flow from top to bottom in the hierarchical control structure, while data signals flow from bottom to top, so that each controller has the necessary information to send appropriate control signals. The main data that needs to be delivered from bottom to top includes active and reactive power availability and energy stored in the battery, among other ancillary information. A detailed explanation of the control levels used in this study, together with the variables exchanged between each, will be provided in Chapter 3.

2.6 Grid Code Requirements

Grid Codes are technical specifications that define all the requisites that a certain facility needs to meet in order to be connected to the grid. They address topics such as a plant's tolerance over frequency and voltage deviations, power quality, control and regulation, protection, and data communication [25]. These requisites are typically technology and size-dependent, and they are the result of a trade-off between the interests of power plant developers and system operators.

Ideally, TSOs would be delighted to have full flexibility from generators available, so the grid is as robust as possible against imbalances, faults, or any other potential issue that may arise. On the other hand, strengthening the power plants against adverse conditions normally increases the CAPEX and OPEX of the plant, which is exactly what developers would avoid if possible. In front of this situation, Grid Codes stipulate reasonable specifications to reinforce the power system against imbalances and faults while considering technology- and size-dependent technical features of power plants.

Every State has its own Grid Code with certain particularities in terms of definitions and technical requirements. Power plant developers need to consider the Grid Code that applies in the region where they want to build and operate an asset, and they are responsible of ensuring that the plant will comply with all the specifications indicated. Failing to meet these requirements implies that the TSO will refuse to allow the connection of the plant to the public grid. Therefore, an important part of the Engineering, Procurement and Construction (EPC) management of a project is to purchase and install all the necessary equipment in such a way that the plant becomes robust against compliance issues.

So, dealing with distinct technical requirements in each country can be a costly and tedious task for manufacturers and project developers. Fortunately for the EU countries, the European Commission requested ENTSO-E to prepare a uniform Grid Code framework for Europe. The outcome of this was the European Network Code Requirements for Generators (RfG), which was published on April 2016. This document *"...helps to ensure fair conditions of competition in the internal electricity market, to ensure system* *security and the integration of renewable electricity sources, and to facilitate Union-wide trade in electricity."* [47].

This Code harmonizes definitions and rules for grid connection of generators across the EU, but TSOs are responsible of implementing the specific parameters of the requirements in the national Grid Codes, always within the ranges indicated in the RfG. In other words, the RfG provides standard rules and definitions, as well as open specification ranges, which TSOs used later as a reference to update their Grid Codes with the nomenclature proposed and defining specific requirements within the given ranges.

Two important definitions provided in the RfG are:

- Power Park Module (PPM): A PPM is a *"unit or ensemble of units generating electricity, which is either non-synchronously connected to the network or connected through power electronics"*. Therefore, this concept applies to WPP (with wind turbines of Type 3 and 4), SPP and BESS.

- Synchronous Power-generating Module: This is *"an indivisible set of installations which can generate electrical energy such that the frequency of the generated voltage, the generator speed and the frequency of network voltage are in a constant ratio and thus in synchronism."*. This concept applies to thermal power plants with synchronous generators, for example.

The technical requirements for the generators depend on whether the unit falls under the category of PPM, Synchronous Power-generating Module, or offshore PPM.

TSOs from the EU countries have taken these guidelines and adapted their Grid Codes accordingly. As a matter of example, the Danish Grid Codes used to include separate technical regulations for solar [48] and wind [49] facilities, with particular specifications applied to each type of power plant. However, this distinction does not exist anymore, since wind, solar and electrical storage assets fall now under the category of PPM, and therefore they share the requirements.

Source [25] has been analyzed to study the technical specifications with regards to reactive power and voltage control that apply to PPM in Denmark. In the absence of specific requirements for HPP, [25] is taken as a reference, assuming that, using only technologies that would be classified as PPM, the whole HPP would also fall into this category.

Danish Grid Codes differentiate between four main categories with respect to the plant's capacity and nominal voltage at the PoC, as per Table 2.3. Normally, more demanding requirements apply to larger plants. According to this table and having a nominal capacity of 170 MW, the HPP of this project would fall into Category D.

Table 2.3: Categories of Power Plant Modules according to Danish Grid Codes [25]

Category	Capacity
A	$0.8kW < P \leq 125kW$
B	$125kW < P \leq 3MW$
C	$3MW < P \leq 25MW$
D	$P > 25MW$ or $V_{PoC} > 110kV$

.

2.6.1 Frequency and Voltage Operation Ranges

Grid Codes indicate the ranges of frequency and voltage within which power plants must remain connected to the grid, either in normal or abnormal operation. For abnormal operation, indications denote the minimum time period they must stay online. Beyond this, if the fault has not been cleared and the values of frequency or voltage are still anomalous, disconnection from the grid is allowed to prevent problems in the power plant and potential damages to equipment.

The tolerance ranges specified in [25] distinguish between plants connected to the transmission grid and distribution grid, as well as assets located in DK1 and DK2[8]. The HPP modelled here is supposed to be connected to the TSO, with a nominal voltage at the PoC of 132 kV. So, Figures 2.13 and 2.14 depict the tolerance ranges for a facility connected to the transmission system with a nominal voltage between 100-300 kV in DK1 and DK2, respectively.

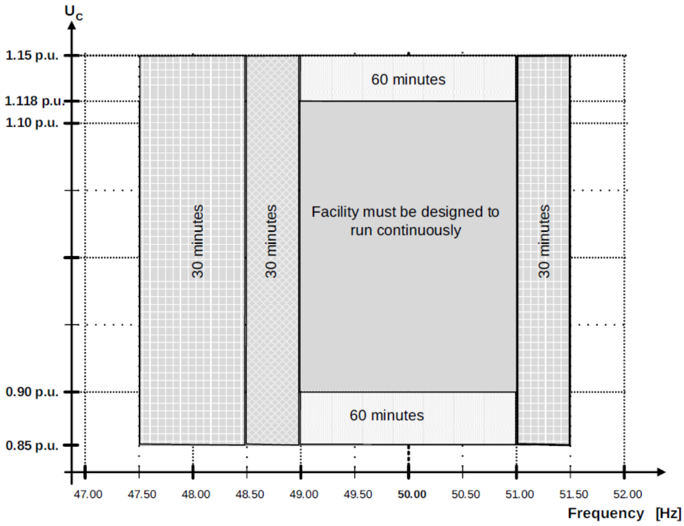

Figure 2.13: Frequency and voltage tolerance applied to PPM connected to the transmission grid in DK1. 100-300 kV. Taken from [25].

[8]Denmark's power grid is divided in two zones, namely DK1 (West) and DK2 (East). DK1 is part of the Continental Europe Synchronous Area, while DK2 is part of the Nordic Synchronous Area.

Starting for the DK1 case, a plant must remain connected continuously as long as the frequency is within 49.00 and 51.00 Hz and the voltage at the PoC is within 0.9 and 1.118 pu. Within this frequency range, the plant must remain connected for one hour if the voltage is between 1.118 - 1.15 pu, or 0.85 - 0.9 pu. When there is an overfrequency between 51.00 and 51.5 Hz the plant must remain connected for at least 30 minutes. The same applies if the frequency falls between 48.00 - 49.00 Hz, or between 47.50 - 48.00 Hz. However, in no case the plant must remain connected for more than 60 minutes if the frequency is below 49.00 Hz.

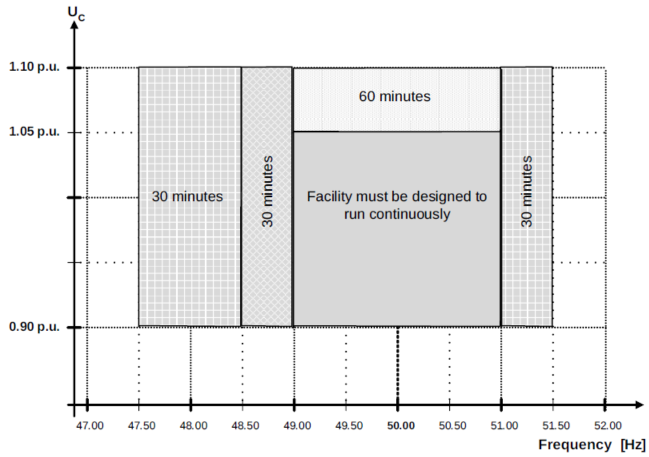

Figure 2.14: Frequency and voltage tolerance applied to PPM connected to the transmission grid in DK2. 100-300 kV. Taken from [25].

Regarding the DK2 case, a plant must stay online provided the frequency is between 49.00 and 51.00 Hz and the voltage is within 0.9 and 1.05 pu. For this frequency range, it must stay connected for at least 60 minutes if the voltage is between 1.05 and 1.10 pu. For overfrequencies and underfrequencies, the same requirements as for the DK1 case apply.

2.6.2 Active power control requirements

Since the project studies reactive power and voltage control, active power requirements will be briefly mentioned in this section while Subsection 2.6.3 will address reactive power control requisites in greater depth. Further information on active power and other aspects of the Danish Grid code with respect to PPM can be consulted in [25].

WPPs and SPPs of categories A2, B, C and D must all provide downwards Frequency Response. This is an automatic downward regulation service to stabilize frequency when it is above the nominal value of 50.00 Hz. It corresponds to FFR in ENTSO-E's standard nomenclature[9]. Moreover, all SPPs of type C and D, and all WPPs of type D must be

[9]Both are comparable due to timing requisites, but FFR can be upwards too.

able to provide Frequency Control[10], which is a droop-based control strategy to adjust active power generation according the frequency value on an automatic, continuous basis. This service is equivalent to FCR, as per ENTSO-E's nomenclature.

PPM of category D must provide Frequency Response This is an automatic regulation service to stabilize frequency when its value deviates from 50.00 Hz through a very fast response. It corresponds to FFR in ENTSO-E's standard nomenclature. Likewise, they must also be able to provide Frequency Control, although the service cannot be activated unless prior agreement with the TSO has been made. This service is comparable with FCR as per ENTSO-E's standard nomenclature.

All the specific parameters detailing how Frequency Response and Frequency Control must be executed (timing, droop values, trigger values, etc.) are depicted in the Technical Regulation, as cited above.

In addition to this PPM within any category are required to include an absolute power limiter function, which is used to receive and implement active power limitations sent by the TSO in real time to manage critical situations of overloading in the public grid. More advanced active power constraints are required for large power plants, as indicated in the correspondent Technical Regulations.

2.6.3 Reactive power control requirements

This section will address the requisites on reactive power and voltage control applied to wind, solar and storage assets within a relevant Category for the project.

PPM must be equipped with reactive power and voltage control functions which control the reactive power supplied by the facility to the public grid via activation orders to control the voltage in the Voltage Reference Point (VRP). This can be the PoC, the PCC or any point in between, and its location is chosen by the relevant Distribution System Operator (DSO).

There are three main control functions within this topic: a) Specific Reactive Power, b) Power Factor and c) Voltage Control. The functions are mutually exclusive, meaning that only one of them can be activated at a time. The parameter settings for reactive power and voltage control functions will be determined by the DSO in collaboration with the TSO.

Reactive Power Control

This function controls the reactive power generated or absorbed by the power plant independently of active power in the PoC. The response to a specific reactive power set-point must start within 2 seconds since the reference is received, and it must be achieved no later than 10 seconds after. This can be represented as an horizontal line in a P-Q chart, as depicted in Figure 2.15, so that the reactive power output from the plant is the same regardless of the active power generation.

[10]It must be noticed, though, that a plant must not perform Frequency Control without prior specific agreement with the TSO

Power Factor

This function controls reactive power proportionally to the active power measured at the PoC. The response must start within 2 seconds since the reference arrives, while it must be effectively achieved no later than 10 seconds after. This is represented as a line with a certain slope in a P-Q chart (Figure 2.16). The slope of the line equals $tan(\phi)$, where $cos(\phi) = PF$.

Voltage Control

This function controls the voltage in the VRP by adjusting the exchange of reactive power between plant and public grid. The plant receives a set-point for the voltage in the VRP and must start and finish the response no later than 2 and 10 seconds since then, respectively. The plant must be capable of performing the control with the droop value configured, as depicted in Figure 2.17

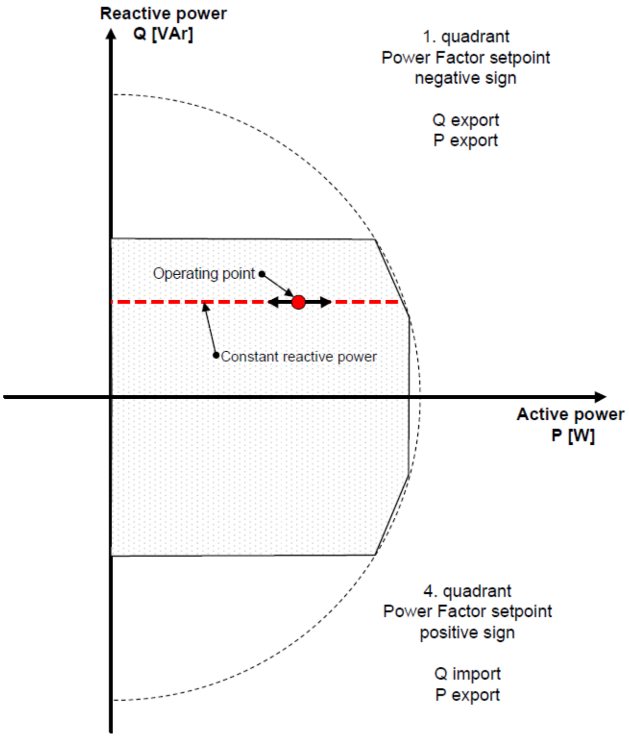

Figure 2.15: Representation of the Specific Reactive Power control function. Taken from [25].

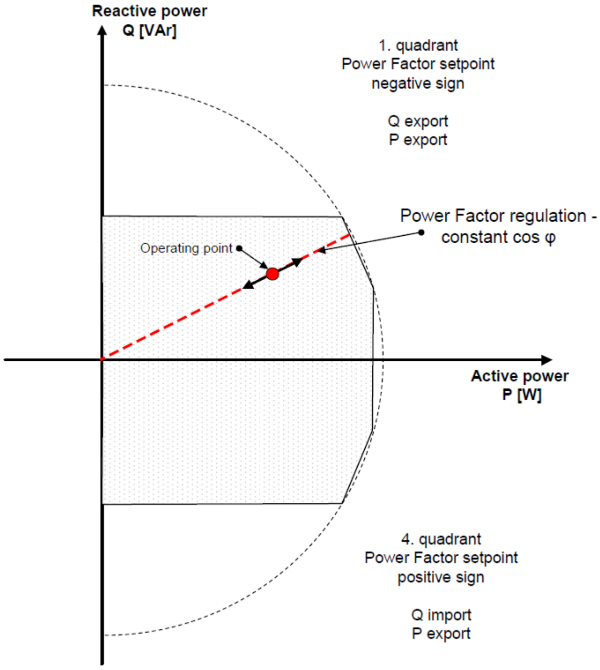

Figure 2.16: Representation of the Power Factor control function. Taken from [25].

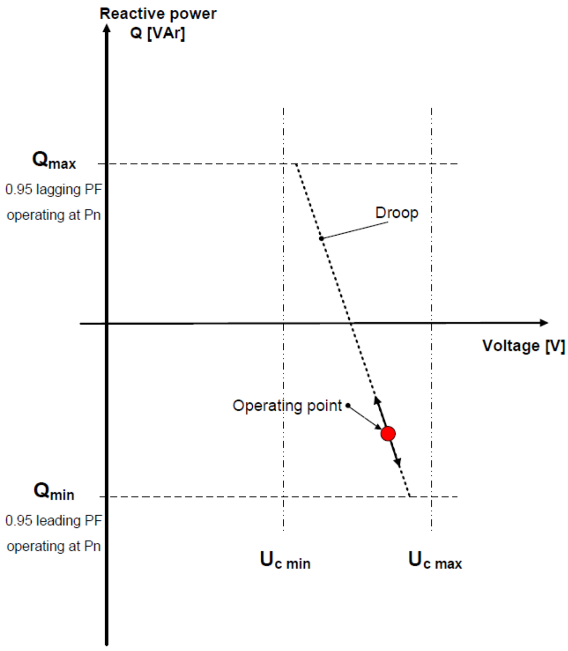

Figure 2.17: Representation of the Voltage control function. Taken from [25].

PPM within Category D must be able to provide Reactive Power Control, Power Factor

Control and Voltage Control. However, by default, the plant must be configured with Reactive Power Control with a value of 0 VAr. A PPM must not carry out voltage control unless an agreement with the DSO has been placed.

The design of the plant must be performed in such a way that the plant can work at any point in the given area presented in Figure 2.18, which is a P-Q chart. So, for specific values of active power, the reactive power that the plant must be able to produce is capped by a maximum and a minimum value. Likewise, Figure 2.19 represents the limitations of the set-point given different values of the voltage at the PoC when the plant is producing maximum power (rated capacity or 1 pu).

So, according to both figures, a PPM must be able to inject or absorb up to 0.329 pu of reactive power, measured at its PoC, under different circumstances. If looking at Figure 2.19, it can be seen how this is actually a particular case of Figure 2.18, where the plant is producing its rated capacity (upper boundary of Figure 2.18. Since the voltage level at the PoC can impact the reactive power capability of the plant (particularly, the converter voltage constraint) this figure will be used to assess whether the HPP modelled in this project meets the Grid Code requirements or not.

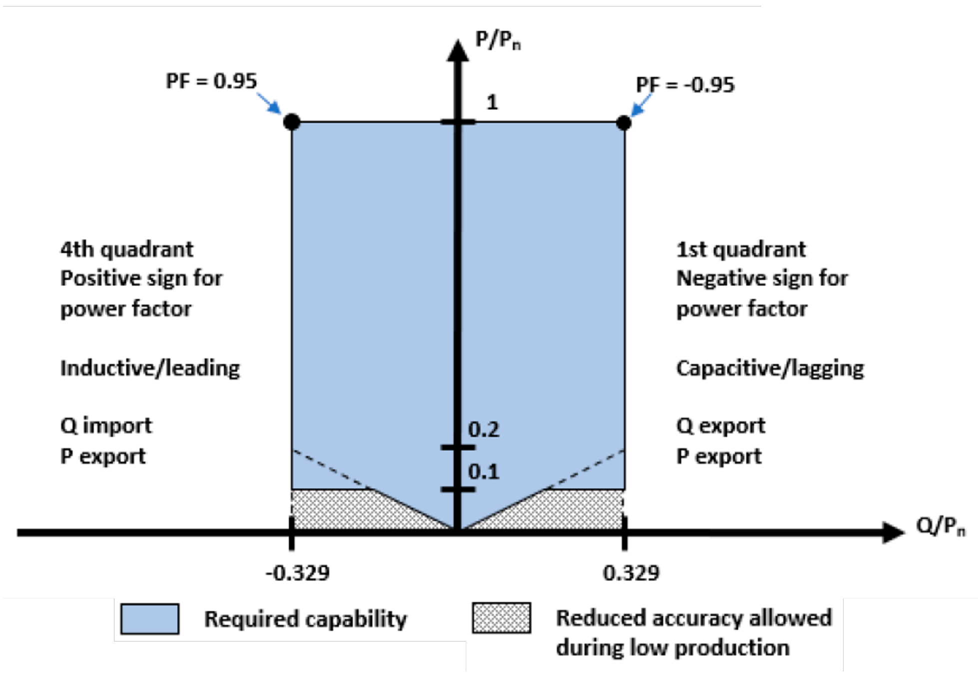

Figure 2.18: Requirements for the delivery of reactive power as function of active power for Category D PPM. Taken from [25]

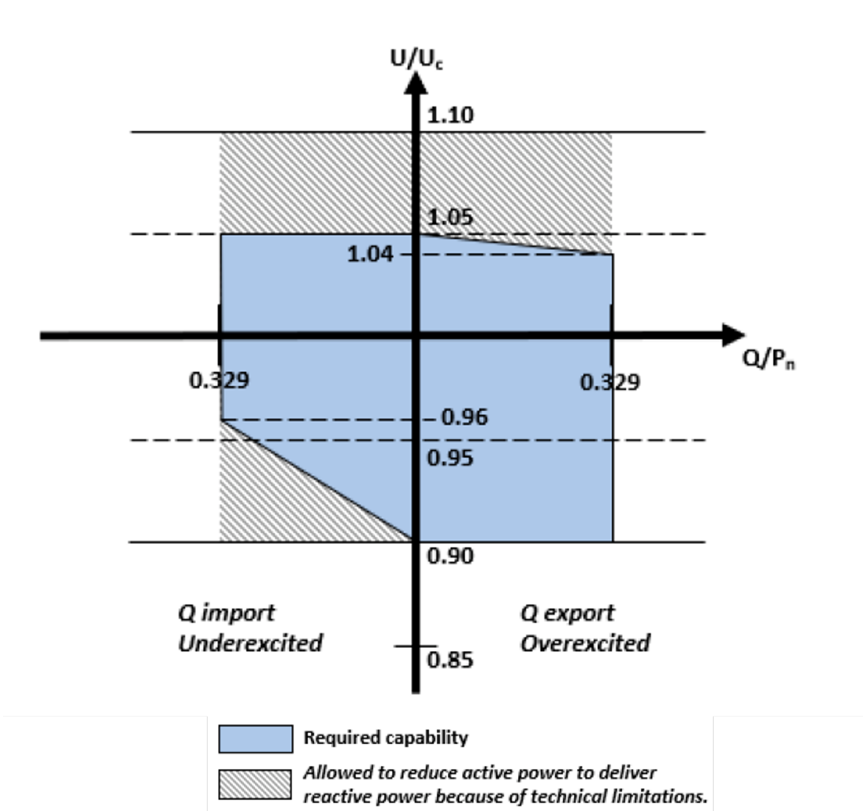

Figure 2.19: Requirements for the delivery of reactive power as function of the voltage in the PoC for Category D PPM. Taken from [25].

3 Modelling and Control

3.1 General Description and Approach

To develop and validate the control architecture, a model in MATLAB/Simulink has been used. The starting point was to take an existing model of an HPP, mainly developed by Qian Long. This model was used for the study [44], which focuses on active power management based on the results of auctions in various electricity markets (i.e., Day-Ahead, Hour-Ahead and Balancing Markets). It was developed following a hierarchical control structure, similar to the proposal from [46]. However, the Q-V control loop was missing, so the HPP was not ready to receive, process and distribute a certain reactive power set-point among the assets.

The starting version included all the models for the wind turbines, solar PV panels, inverters and batteries, as well as the interactions between the different control levels and an advanced active power control architecture to provide frequency regulation. Particularly, the model was prepared to simulate the provision of FFR, FCR and automatic Frequency Restoration Reserve (aFRR, or Secondary Reserve).

However, the model lacked an internal and external grid to study the interaction between HPP and the power system it is connected to. The reason is that [44] focuses on the internal control architecture and the interaction between the various control levels. This project, on the contrary, aims at evaluating the impact of the HPP over the grid voltages and power flows, so modelling the internal and external lines and transformers is of imperative relevance.

So, to transform this starting version into something suitable for the purpose of the study, all the changes performed were divided in two main blocks:

- **Adding the Q-V control loop.** This included the addition of a hierarchical control architecture which receives a certain set-point and distributes reactive power references among the assets in parallel to the existing active power control loop. The novel control architecture includes three control levels and two control functions.
- **Adding internal and external grids.** Using the libraries and blocks provided in the Simulink's extension Simscape Electrical (formerly known as SimPowerSystems and SimElectronics), the main electrical components within and outside the plant were added.

The starting HPP model with the newly implemented features was connected to the grid model by using Simulink's built-in Dynamic Loads. One block is used to represent each power module (WPP, SPP and BESS). The Dynamic Load block takes as input the set-points for P and Q and consumes (or generates) power accordingly. So, the signals containing the P and Q outputs of each power plant in the HPP model were the inputs to the corresponding Dynamic Load block. This way, the dynamic behavior of the plant and the control system is linked to the grid, so that any change in the power output of the plant is passed through the external grid. Moreover, the measurements of voltages and reactive power in selected buses of the grid are sent to the HPP model for control purposes. This is depicted in Figure 3.1.

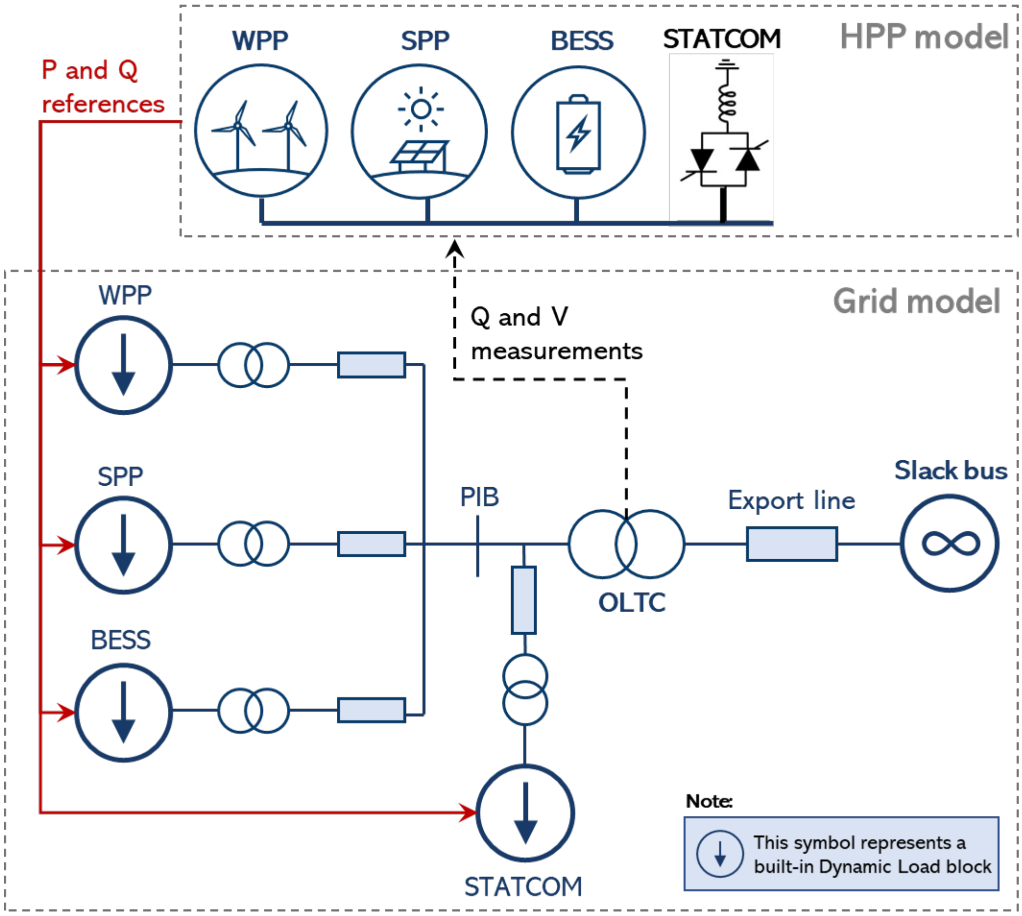

Figure 3.1: Overall schematic representation of the dynamic model. Own elaboration.

Three scenarios are implemented to assess the reactive power capability of the plant with different set-ups, where each scenario represents a particular degree of ownership of the grid. According to the Danish Grid Codes, the PoC is the reference bus for Q measurements, so by selecting a different location for the PoC on each scenario different degrees of ownership are represented, and Q capability under each ownership scenario can be assessed. The point PIB stands for Plant Interconnection Bus, and represents the point where all the collections systems from the three power plants are linked together. This point happens to meet at the PoC for Scenario 1.

In principle, owning the highly inductive overhead lines and transformers should negatively impact the reactive power injection capability (as the plant itself would be very inductive). However, this also allows to place support devices such as STATCOMs closer to the PCC, and this in return should enhance voltage control over such bus. More details about the set-up of the scenarios and the location of the STATCOM can be found in Section 3.4.

The data used for the lines was taken from [50] and [30], and it is showed in Table 3.1. Table 3.2 shows the main characteristics of the transformers used in the model. The numbers are taken from the default parameters of a three-phase transformer block in Simulink due to difficulties in getting more accurate, suitable data for the specific transformers used in the model. Lastly, Table 3.3 shows the nominal capacity of each plant and the parameters used to calculate the reactive power capability of the plant. The data is taken from [32] and due to difficulties in getting specific equivalent impedances for the SPP and BESS, the same numbers were taken for all the plants.

Table 3.1: Line parameters used in the model.

Name	V_{Nom}(kV)	R (Ohm/km)	L (H/km)	C (nF/km)	l (km)
WPP line	33	0.069	0.00132	8.8	2
SPP line	33	0.069	0.00132	8.8	2
BESS line	33	0.069	0.00132	8.8	2
Export line	132	0.063	0.00267	22.48	20

Table 3.2: Transformer parameters.

Name	$V_{LV,Nom}$(kV)	$V_{HV,Nom}$(kV)	X_{cc}(pu)	S_N(MVA)
WPP trafo	0.69	33	0.08	150
SPP trafo	0.69	33	0.08	50
BESS trafo	0.69	33	0.08	11
STAT trafo	0.69	33 or 132	0.08	Variable
OLTC Trafo	33	132	0.08	200

Table 3.3: Power plant capacity and parameters for Q capability calculation.

Name	P_{Nom} (MW)	$V_{C,MAX}$ (pu)	$V_{C,min}$ (pu)	$I_{C,MAX}$ (pu)	R_{eq} (pu)	X_{eq} (pu)	B_{eq} (pu)
WPP	120	1.1	0.8	1.1	0.0196	0.14	0.021
SPP	40	1.1	0.8	1.1	0.0196	0.14	0.021
BESS	10	1.1	0.8	1.1	0.0196	0.14	0.021
STAT	Variable	1.1	0.8	1.1	0	0.07	N/A

3.2 Control architecture

The control architecture developed for this model is inspired by the hierarchical control architecture proposed in [46]. In this section, the Q-V control loop architecture is explained in detail. However, the P-f control loop had been implemented beforehand, and it is out of the scope of this project. Therefore, the details behind the P-f control loop are omitted[1].

Three control levels are defined: 1) HPP Controller, 2) Plant Controller, and 3) Asset Controller. The roles, functions, most relevant blocks and main variables within each controller are described in the following subsections.

No EMS Controller is included since the main function of this system is to optimize bid submissions to energy markets to maximize the plant's revenue from power sales. This has limited impact in reactive power and voltage control, which are ancillary services that the plant performs following TSO's or DSO's indications. On the other hand, one could argue that the active power generated limits how much room for reactive power there is, so EMS optimizing strategy does have a relevant impact on reactive power management. However, in this project active power is taken as a given condition rather than a variable, so that Q capability is tested with different levels of P. Therefore, it would not make sense to spend efforts in modelling the EMS Controller for the purpose of this study.

Two control functions are implemented: Q control and V control. The HPP Controller is the only system that changes according to the control function selected. A Proportional-Integral (PI) Controller is used for the Q control function, while a droop-based controller is used for the V control function.

3.2.1 HPP Controller

The HPP Controller receives external orders from the relevant TSO or DSO. In this case, the orders can be either a specific Q set-point or a reference value to control the voltage at the VRP, depending on the control function triggered. Then, making use of a reactive power dispatch algorithm, the controller distributes specific reactive power set-points to each of the power plants.

As depicted in Figure 3.2, the HPP Controller receives the reference and the Q capabilities of each plant (injection and absorption) in real-time. All these variables are the inputs to the dispatch algorithm. It must be noted, though, that the values of Q availability of each power plant come expressed in pu, in each plant's power base. So, the first thing that needs to be done is to change to pu in the HPP power base. This is simply a matter of multiplying each signal by its correspondent plant's power base and dividing by the HPP power base (170 MVA).

After this, the signals are sent to the dispatch algorithm, modelled with a MATLAB function block. The set-up of this algorithm is rather simple, as it dispatches in proportion to each plant's Q capability. First, it calculates total HPP capability at the

[1] Also, for the sake of briefness.

Poc:

$$Q_{CAP,inj,HPP} = Q_{CAP,inj,WPP} + Q_{CAP,inj,SPP} + Q_{CAP,inj,BESS} + Q_{CAP,inj,STAT} \quad (3.1)$$

$$Q_{CAP,abs,HPP} = Q_{CAP,abs,WPP} + Q_{CAP,abs,SPP} + Q_{CAP,abs,BESS} + Q_{CAP,abs,STAT} \quad (3.2)$$

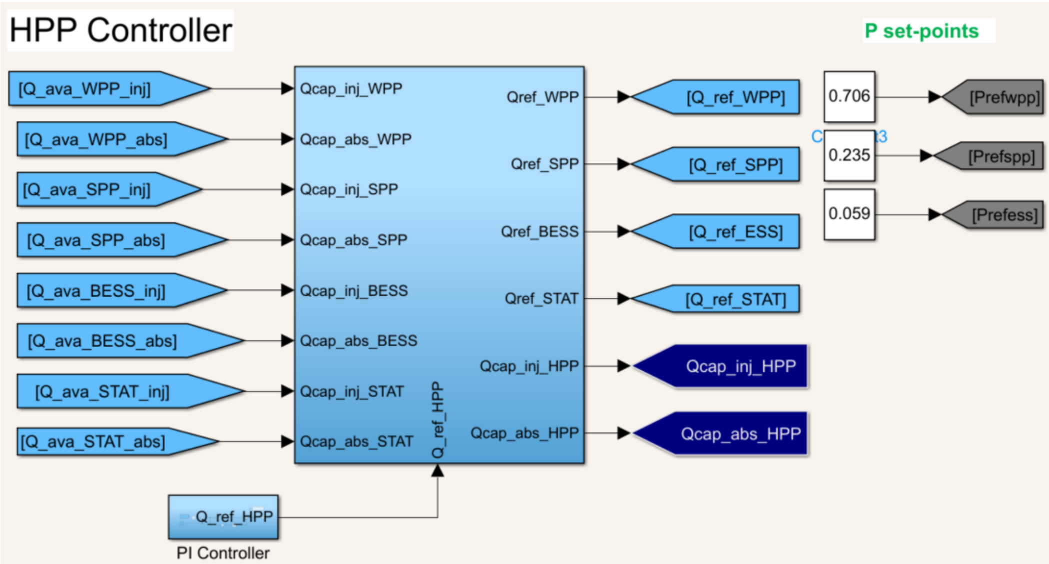

Figure 3.2: HPP Controller. Screenshot from the model in Simulink.

Second, it generates the reference for each power plant based on the overall Q reference received and their capabilities:

$$If \;\; Q_{ref,HPP} > 0 \Longrightarrow Q_{ref,i} = Q_{ref,HPP} * \frac{Q_{CAP,inj,i}}{Q_{CAP,inj,HPP}} \quad (3.3)$$

$$If \;\; Q_{ref,HPP} \leq 0 \Longrightarrow Q_{ref,i} = Q_{ref,HPP} * \frac{Q_{CAP,abs,i}}{Q_{CAP,abs,HPP}} \quad (3.4)$$

The output references are not capped, so the reference for a plant could be greater than its capability. However, downstream controllers make sure that the limitations of each asset are respected.

Regarding active power control, all the existing controllers have been removed for simplicity, and to reduce the compilation and simulation times. The references displayed in Figure 3.2 (top-right corner) correspond to each of the nominal active power of each plant, in pu using the HPP power base. These values are used for the comparison of the Q capability of the HPP against the Danish Grid Codes, as explained in Section 3.4:

- For the WPP: $0.706 * 170 \approx 120MW$
- For the SPP: $0.235 * 170 \approx 40MW$

- For the BESS: $0.059 * 170 \approx 10MW$

These references are sent to the respective plant controllers.

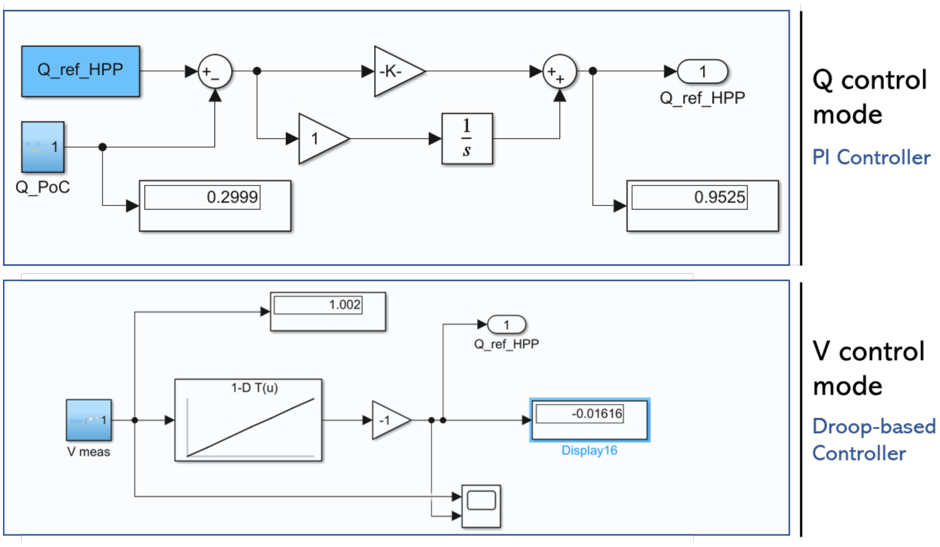

Figure 3.3: PI and droop-based controllers. Screenshot from the model in Simulink.

The Q reference entering the dispatch algorithm is the output from a specific controller depending on the control function triggered. For Specific Q set-points, a Proportional-Integral (PI) controller as the one depicted in Figure 3.3 (top diagram) is used. This controller receives the Q set-point and the actual Q flow at the PoC, computes the error as the difference between both, and delivers a reference value for the overall Q to be produced by the HPP.

This controller is needed to ensure that the Q flow at the PoC follows the given reference. Otherwise, the reference would be followed at the PIB instead (let as call this point Power Interconnection Bus - PIB). However, for Scenario 1 this controller is not needed, as the plants are connected exactly at the PoC.

On the other hand, when working in V-control mode, the controller used is droop-based, as depicted in Figure 3.3 (bottom diagram). In this case, the controller receives the voltage in the VRP, sends it to a Lookup table, which contains all the corresponding set-points for each voltage level. The values on the Lookup Table depend on the droop value selected. For all the simulations the standard droop value of 4% (as indicated in [25]) has been taken. This means that the plant will inject the maximum amount of reactive power when voltage falls below 0.96 pu, and it will absorb the maximum amount of reactive power when voltage raises over 1.04 pu.

The output of this block is the Q reference which is sent to the dispatch algorithm. So, regardless of whether the HPP is working in Q-control or V-control mode, the references exiting the HPP controller are always Q set-points, and the Plant and Asset control levels work in the same way.

3.3 Plant and Asset models

3.3.1 Plant controllers

The plant controllers receive the active and reactive power references, as well as the voltage level at the PIB. The structure of the plant controllers is the same in all scenarios and in all power plants (WPP, SPP and BESS). Figure 3.4 depicts the Q control loop at the plant control level of the WPP. The P control loop is not showed because the focus here is on Q and voltage, but the control architecture is very similar to the Q control loop.

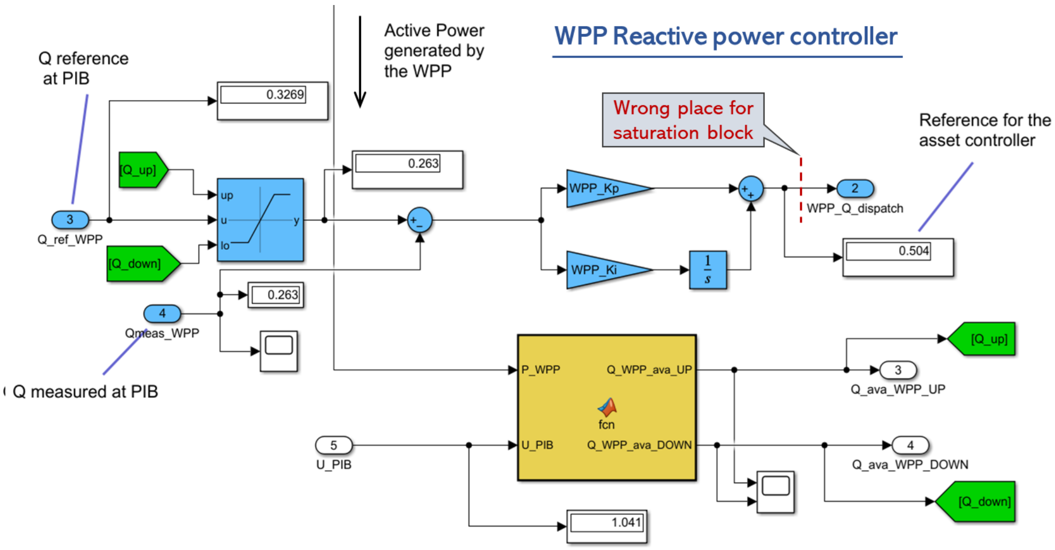

Figure 3.4: Q Plant controller. Screenshot from the model in Simulink.

First, the Q reference arriving from the HPP controller passes through a Dynamic Saturation block, which ensures that the reference does not exceed the Q capability limits of the plant in real-time. This saturation block had been placed at first in the output of the PI controller, but this was found to be a mistake. The problem with this is that the Q set-point sent to the turbine is capped considering the whole WPP limitations, so this approach underestimates the Q capability of the wind turbines, and therefore underuses them.

To better understand this, it is helpful to use an example. Let us say that the Q injection capability of the WPP is 0.3 pu for a given set of conditions (measured at the PIB). If placing the saturation block at the end of the model shown in Figure 3.4, the wind turbine receives the set-point of 0.3 pu, but the measurement of Q at the PIB (after passing through all the cables and transformers) would be somewhere around 0.25 pu. This approach is counting twice the impedances between the wind turbine terminals and the PIB, and therefore placing the saturation block before the PI will make a better use of the resources available.

The Q capability is calculated with a MATLAB function. This function receives the P generated by the WPP and the voltage level at the PIB. It also contains all the relevant parameters to calculate the Q capability, following the procedure explained in Section 2.3 (X_{WPP}, R_{WPP}, B_{WPP}, $V_{C,max}$, $V_{C,min}$ and $I_{C,max}$). The outputs of this function are the injection and absorption capability of the plant ($Q_{CAP,inj,WPP}$ and $Q_{CAP,abs,WPP}$), which are both sent to the Dynamic Saturation block mentioned above, and to the HPP Q Dispatch algorithm.

Second, the filtered Q reference is compared against the Q flow measured at the PIB, and the resulting error enters a PI controller, which sends the output to the wind turbine controller. This Q set-point is sent together with the P set-point, generated in the parallel P control loop. For simplicity, all the variables and parameters in this block are expressed in pu values, using the WPP nominal capacity as power base.

For the sake of briefness and as this configuration is repeated for the SPP and BESS models, it will not be explained again. The only difference are the values of the parameters of each power plant.

3.3.2 Asset controller: Wind Turbine

Figure 3.5 shows the wind turbine controller. The starting version of this model contained all the particular dynamics of a wind turbine, such as a pitch controller, an aerodynamic model and a mechanical model. All these blocks are very useful to study the dynamic behavior of the turbine in front of different wind speed levels. For instance, a block would compare the P reference from the Plant Controller with the P available based on the given wind speed and pitch angle of the blades, compute the minimum and send it to the MSC Controller. However, all these blocks have been commented out[2] to simplify the model and accelerate the computation time (since P control is out of the scope of this project).

Therefore, the active power reference coming from the Plant Controller enters the MSC Controller directly, assuming that there is enough kinetic power available in the wind to follow the reference provided by the plant controller. The MSC Controller is a PI Controller which compares actual P vs P set-point, computes the error and sends a P reference accordingly to the GSC Controller.

[2]Which is equivalent to ”removed”.

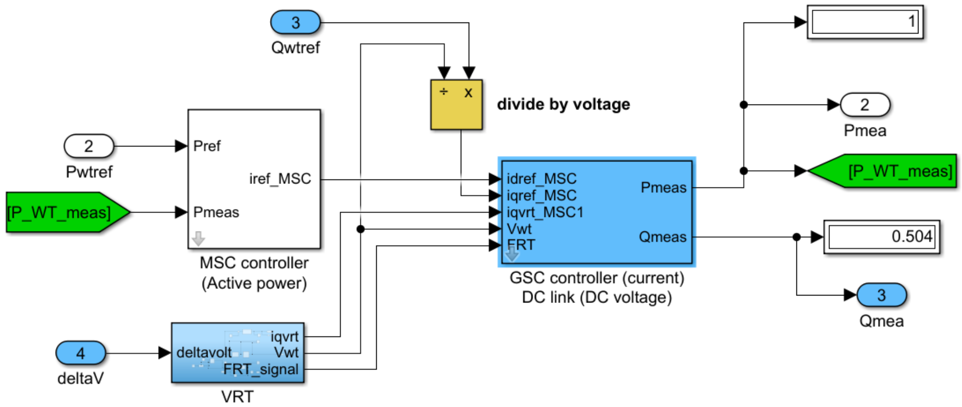

Figure 3.5: Wind Turbine controller. Screenshot from the model in Simulink.

More precisely, this signal is the reference for the direct current $i_{d,ref}$ in the GSC controller, while the input for the quadrature current $i_{q,ref}$ is the Q set-point coming from the WPP controller, divided by the voltage at the wind turbine terminals. Another block addresses FRT, which is an advanced control function to support the power grid during the occurrence of a fault causing abnormally low or high voltages. As this study focuses on static simulations, the analysis of transients like faults is outside the scope of this project, and therefore the FRT blocks will remain inactive[3].

In this configuration, the GSC Controller watches the voltage in the DC link of the back-to-back converters of the WTG, and it also controls the reactive power exchange with the grid. It receives $i_{d,ref}$, $i_{q,ref}$, the voltage level at the turbine's terminals, $i_{qVRT,ref}$ and an FRT signal. These two last signals remain inactive, as the FRT function is not explored here.

The output values of P and Q are the set-points to the Dynamic Load block that is used to connect the WPP model with the grid model. This block will be further explained in Subsection 3.3.7

3.3.3 Asset Controller: PV inverter

Recall that the SPP Controller is modelled in the same way as the WPP Controller, which is explained in Subsection 3.3.1.

The simplified model for the PV asset controller is depicted in Figure 3.6. Similarly to the wind turbine model case, the PV Asset Control level included a model for the PV module which accounted for the available active power that could be produced based on the solar irradiation and temperature values. Then, another block would compare this available power with the P set-point from the SPP Controller. However, and following the idea mentioned before, these blocks have been commented out.

[3]The inactivity of these blocks is achieved by using a null deviation of voltage with respect to nominal value. Notice that voltages in this project will not deviate from 0.9-1.1 pu, while FRT is thought for voltage levels below 0.5 pu or above 1.2 pu, which are maintained during typically 1-2 seconds max.

So, the active power reference sent from the SPP controller enters the Grid Converter block, which essentially accounts for the efficiency of the asset. No FRT block was included in this model, so the control architecture is much simpler than in the wind turbine case. Both the output of the grid converter and the Q set-point provided by the SPP Controller are passed through a transfer function which introduces a slight delay to represent the time taken in the diverse controllers in between. These signals are then sent to the Dynamic Load block which represents the SPP in the grid model.

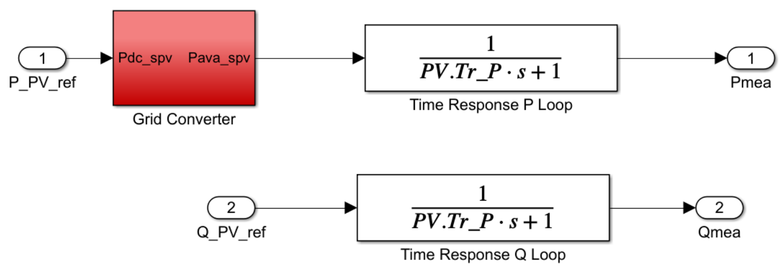

Figure 3.6: PV Asset controller. Screenshot from the model in Simulink.

3.3.4 Asset Controller: Battery

Recall that the BESS Controller is modelled in the same way as the WPP Controller, which is explained in Subsection 3.3.1.

Figure 3.7 shows the Energy Storage system. In this model, the voltage at the battery's terminals is read and multiplied by the $i_{d,out}$ signal to compute the P generated (or consumed) by the storage system.The value of P is sent to the Dynamic Load representing the BESS in the power grid model. The $i_{d,out}$ signal comes from the charge control block. On the other hand, the P control block takes the voltage at the battery's terminals, the P set-point from the BESS controller, and the State of Charge (SOC) of the battery. The output of this block is $i_{d,ref}$, which enters the Charge Control block together with $i_{q,ref}$. The latter comes from the division between the Q reference and the voltage at the battery's terminals.

The Charge Control block models the dynamics behind the charge and discharge of the battery, and it was included in the starting version of the model. The two outputs of this model are $i_{d,out}$ (as previously mentioned) and $i_{q,out}$, which is multiplied by the voltage at the battery's terminals again so that Q generated by the storage system is obtained. This signal is sent as a set-point to the Dynamic Load block representing the BESS in the power grid model, together with the P set-point as mentioned above.

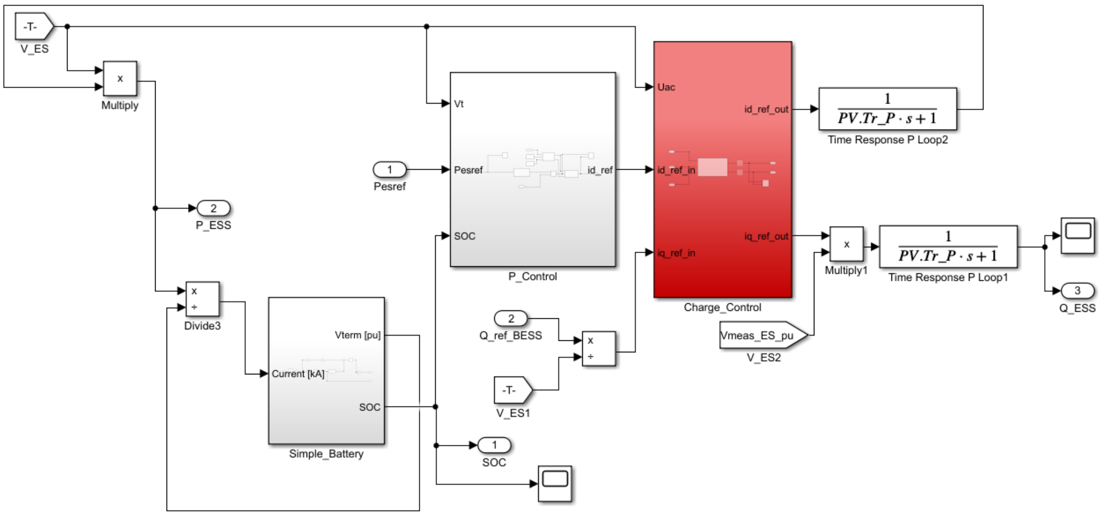

Figure 3.7: Energy Storage Asset controller. Screenshot from the model in Simulink.

3.3.5 STATCOM model

The STATCOM modelling was done with a similar approach as in the power plants' models. Although there is a built-in STATCOM block in Simulink, using it in the grid model was discarded due to technical difficulties. The main problem was too long computation times when trying to run the simulation using this block[4].

The STATCOM is implemented in the power grid by using a transformer and a Dynamic Load whose set-points are driven externally by the STATCOM controller, as explained below.

Figure 3.8 shows the control model for the STATCOM, which is similar to the Plant controllers previously mentioned. The Q reference coming from the HPP Controller is capped with the Q capability of the STATCOM and compared with the Q measurement at the high-voltage side of the STATCOM's transformer. The resulting output error is sent to a PI controller.

[4]The STATCOM block was tested in a simple model with a line, a voltage source, a load and two transformers. All the blocks in this simple model were the same as the ones used in the Simulink's example model provided to test the STATCOM built-in block. However, the problem of too long simulation time could not be solved.

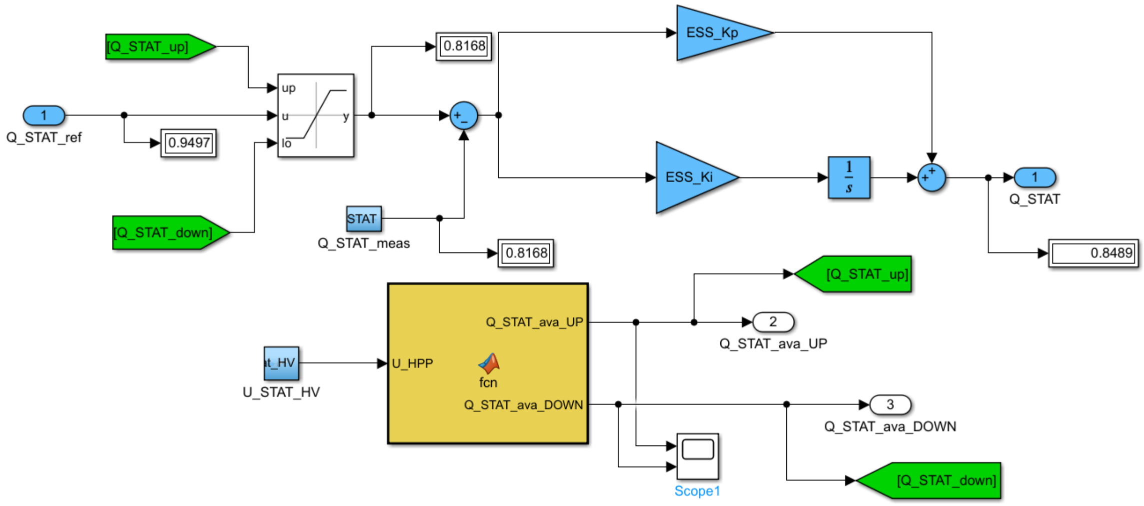

Figure 3.8: STATCOM controller. Screenshot from the model in Simulink.

3.3.6 OLTC transformer model

As in the case of the STATCOM modelling, the built-in OLTC transformer model in Simulink was causing several problems that led to the decision of not using this block in the model. The block was tried first in a very simple model with a voltage source, one simple transformer, a line, the OLTC transformer and a load. Several issues arose, with the most important being an unexpected impact of the tap changes in the voltage levels at both sides of the transformer. The trigger of the tap changer would increase/decrease voltages simultaneously at both sides and would not control the voltage level to the target value.

Having these persistent issues and considering that the focus of this project is on static simulations, it was decided to set the "tap position" manually. So the needed transformation ratio was set before running the simulation, by editing the nominal voltages of the transformer. In particular, the nominal voltage at the low-voltage side (the HPP side) was changed in a range between ±15%. So, having a nominal voltage on the HPP side of 33 kV, the minimum transformation ratio during the simulations is 28/132 kV (or 0.212), while the maximum transformation ratio is 38/132 kV (or 0.288). The nominal transformation ratio is 33/132 kV (or 0.25).

Even though this approach could be not the most elegant, it has proven to be as effective as simple, as the model runs very fast (approximately 1 second per simulation) and it is trivial to iterate until the desired voltage level is achieved (always respecting the maximum and minimum transformation ratios).

3.3.7 Grid model

As explained in the previous subsections, the models of each power plant containing the Plant Controllers and Asset Controllers are connected to the grid by means of Dynamic Load blocks (one per plant). This block consumes the set-points of P and Q given as inputs. So by sending the resulting P and Q of each power plant model to its corresponding Dynamic Load block, the plant model is integrated with the grid model. It must be noted, though, that the sign criterion is different for loads and generators. For a load, positive signs are associated with a consumption of P and an inductor-like behavior (absorption of Q), so there needs to be a change of sign between the output signals coming from the plant models and the Dynamic Load blocks. This is exemplified in Figure 3.9, where a Gain block with the value -1 reverts the sign of the set-points entering the Dynamic Load block. This figure depicts the electric model of the WPP, and the exactly same structure has been used for the SPP and BESS models.

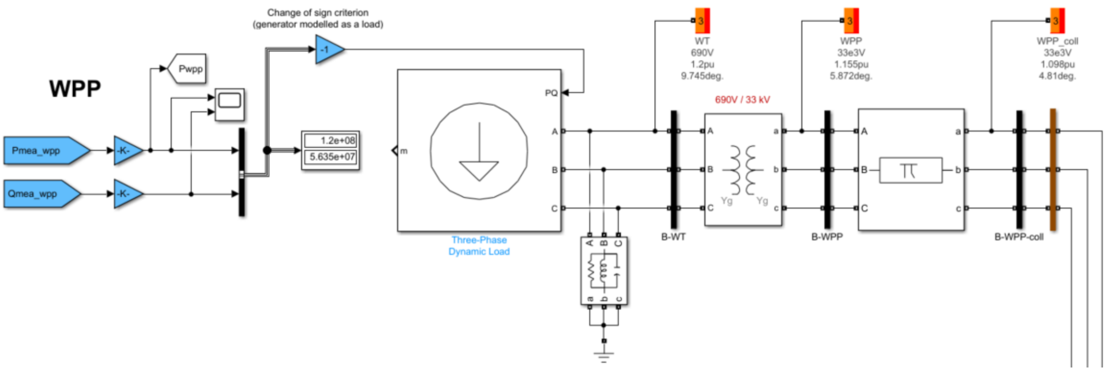

Figure 3.9: WPP electric model. Screenshot from the model in Simulink.

The Dynamic Load is representing all the wind turbines within the WPP. The P and Q set-points are sent from the WPP model in pu, so a gain block is used to change to W and VAr, respectively.

Each of the turbines includes a step-up transformer, which increases the voltage from 690 V to 33 kV. All these transformers are represented by the single 0.69/33 kV transformer depicted in Figure 3.9. A Three-Phase RLC parallel branch is added between the Dynamic Load and the transformer. This is a parallel branch with a very high resistance (1 MΩ) and inductance (1 MH) that needs to be added in order to prevent an error in Simulink. The error message says that the Dynamic Load is modelled as a current source, and therefore it cannot be connected in series with the inductive element, in this case, the transformer. Adding this very high impedance in parallel solves the issue.

A Three-phase Pi section line of 2 km represents the collection system carrying the current from the turbines' terminals to the PIB. The thin block colored in brown at the end of the diagram is a negligible line of only 1 meter, whose only function is to differentiate between the end of the WPP collection system and the PIB. This is needed to measure the power flows at the end of the WPP collection system, since in the absence of this short line, this point would be exactly the same as the PIB, and therefore the power flow measured would be not only coming form the WPP, but also from the SPP and BESS.

Another relevant consideration here is that the voltage values at the wind turbine terminals and at the HV side of the transformer should not be taken as indicative of what they would look like in real life. In the model, the single transformer represents all the wind turbine transformers, and therefore a huge flow of reactive power goes through it. In reality, the reactive power flowing through each transformer would be much smaller (since it would be produced by one single WTG). Therefore, the impact on the voltage levels at both sides of the transformer would be much weaker. In other words, if when injecting a large amount of reactive power the voltage in the LV side of the transformer is somewhere around 1.2 pu, this does not mean that there is an error or that the solution is unfeasible, but it is a consequence of how the WPP is modelled.

On the other hand, Figure 3.10 depicts how the STATCOM is connected to the grid. This is done following the same approach as with the power plants. There are only two differences between the electric model of power plants and STATCOM. The first difference is that there is no line in the STATCOM model, as it is assumed that the STATCOM would be connected directly to the line, with no impedances in between. The second difference has to do with active power: as there should be no P generated by the STATCOM, a constant of value 0 is sent as P reference to the Dynamic Load.

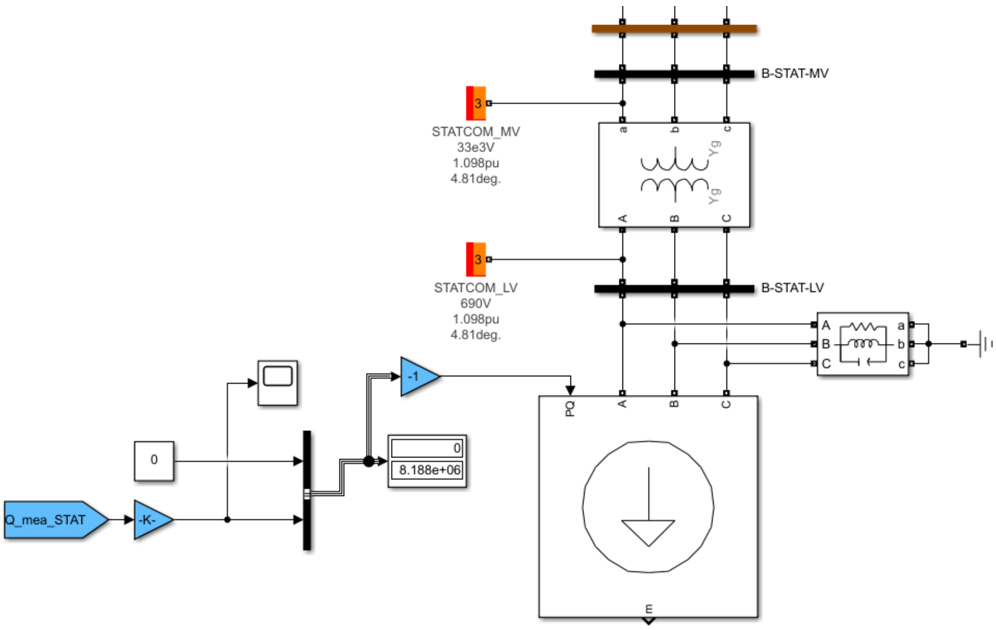

Figure 3.10: STATCOM electric model. Screenshot from the model in Simulink.

This whole model is placed in different locations across the grid, depending on the Scenario. The only change to be performed is to adapt the nominal voltage at the HV side of the transformer according to the Scenario. For Scenario 1, the STATCOM is connected to a 33 kV bus, and therefore this is the nominal voltage that applies to the HV side of the transformer. For Scenarios 2 and 3 the STATCOM is connected to a 220 kV bus, so this needs to be nominal voltage of the HV side of the transformer.

Figure 3.11 shows the PIB, where all the power plants and (in this case) the STATCOM are connected; the OLTC Transformer; the Export Line; the PCC and the connection with the rest of the grid. The set-up shown in this picture corresponds to Scenario 1. Slight adjustments are performed for the other two scenarios, as explained in Section 3.4. The PIB and PoC happen to meet at the same point for this scenario.

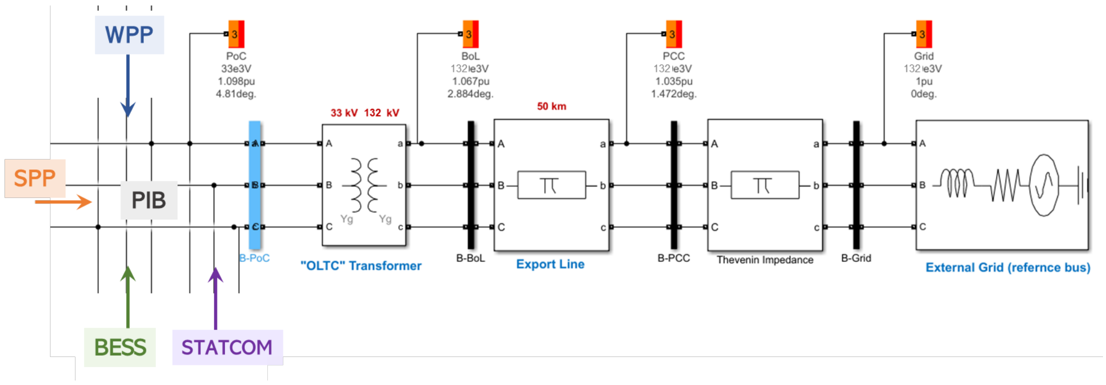

Figure 3.11: Export line, OLTC Transformer, PCC and external grid. Screenshot from the model in Simulink.

The PIB is connected to the OLTC Transformer (recall that this is modelled as a normal transformer whose transformation ratio is changed manually for each simulation). The OLTC Transformer is then connected to the 50 km Export Line, which leads into the PCC. To simulate the external grid, a Voltage Source with another line has been used. The Voltage Source acts as slack bus and controls the voltage on the point B-Grid to 1 pu. The additional line separating this point from the PCC is used to enable controllability over the voltage at PCC. In the absence of this line, the Voltage Source influence over the PCC would be too large, and the voltage would be always 1 pu, regardless of what happened in the rest of the model.

3.4 Scenarios

This section will present a full description of the Scenarios used in this project, highlighting the differences between each. Figure 3.12 provides an overview of the Scenarios and the relevant changes from one to another.

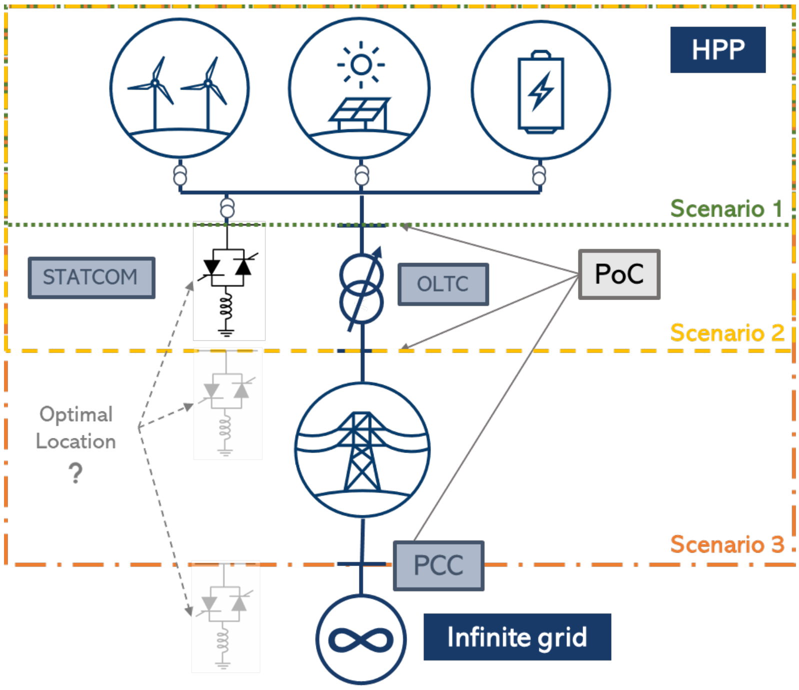

Figure 3.12: Overview of the 3 different Scenarios studied in this project. Own preparation.

The main aspect of the approach that changes among the diverse scenarios is the ownership of the assets in the grid and the location of the STATCOM. Recall that in Section 1.2 one of the objectives mentioned was *"To analyze the impact of the ownership of the line and the location of reactive power sources on the plant's capability"*. In principle, owning more transformers and lines increases the "inductor-like" character of the plant, which reduces the injection capability since these assets act as Q sinks in normal operating conditions. On the other hand, the boundaries of the HPP are expanded when the line is property of the plant owners. This opens the door to install ancillary devices such as STATCOMs closer to the PCC, thus enhancing voltage control over this point.

So, to represent different degrees of ownership in the grid, the PoC is placed on different locations. This has an impact on the controllability of the OLTC transformer, and also on the potential locations for the STATCOM. For simplicity, the STATCOM has been placed in all Scenarios at the PoC. This makes sense from a technical point of view, since the less lines there are between the STATCOM and the PoC, the less Q would be consumed by such lines, and therefore the more Q is effectively delivered at the PoC[5].

For each scenario, the Q capability of the HPP will be compared with the Danish Technical Regulation specs without considering the addition of the STATCOM. In cases where

[5]Which is the point where Q is measured for compliance concerns.

the HPP has not enough capability, the capacity of the STATCOM will be increased until the Danish specs are met for the most demanding conditions.

Starting from Scenario 1, as mentioned above the PoC happens to meet at the PIB. This means that the OLTC transformer belongs to the relevant TSO/DSO, who will control it in real-time. The Q capability of the HPP is then characterized at the LV side of the OLTC transformer, and this is also the chosen location for the STATCOM. Recall from Subsection 3.2.1 that this scenario is the only one which does not need for a PI controller at the HPP control level. This is because the PIB and the PoC are the same, so the plant controllers make sure that the overall Q delivered at the PoC follow the Q set-point provided. The other two Scenarios require an additional PI controller at the HPP control level due to having different locations for PIB and PoC.

In principle, this scenario should be the less favorable in regards of both Q capability, as the lack of control over the OLTC transformer can lead to internal voltage levels at the plan which limit the Q capability of the plants (this affects the voltage limitations as developed in Section 2.3).

In Scenario 2, the OLTC transformer belongs to the HPP owners, and therefore it is controllable by the HPP operators. This should enhance the Q capability of the plant, although having the export line in between the PoC and the PCC may limit the voltage controllability at the PCC, since the STATCOM would be installed at the HV side of the OLTC transformer.

Lastly, in Scenario 3 both the OLTC transformer and the export line belong to the HPP owners, allowing for controllability on the OLTC transformer and enabling the installation of the STATCOM at the end of the line. The Q capability is expected to be limited as compared with Scenario 2 because of the inductor character of the export line. However, voltage control over the PCC may be better since the STATCOM is much closer to the delivery point in this case.

The specific features of each scenario are summarized in Table 3.4:

Table 3.4: Specific features by Scenario.

Scenario	**1**	**2**	**3**
PoC	Same point as PIB	HV side of OLTC. (Beginning of Line)	PCC. (End of Line)
OLTC	Owned and controlled by TSO/DSO.	Owned and controlled by the HPP operators.	Owned and controlled by the HPP operators.
Export line	Owned by the TSO/DSO	Owned by the TSO/DSO	Owned by the HPP operators
STATCOM	Located at PoC (PIB)	Located at PoC (BoL)	Located at PoC (PCC)

4 Results and Discussion

This Chapter presents the results of the various simulations carried out with the model using the three scenarios previously presented. The first section addresses the validity of the HPP and the control mode used to meet the Danish Grid Code requirements regarding reactive power capability of the HPP.

The second section focuses on the voltage control function. The ability of the HPP to control voltage at the PCC is analyzed for the three scenarios.

4.1 Validation of the HPP to meet Q-related requirements in the Danish Grid Codes

As explained in Section 2.6.3, in order to be eligible for the connection with the public grid, the HPP needs to be able to exchange a certain amount of reactive power with the grid, under particular conditions. The frequency and voltage tolerances of the plant will not be studied here, as that is related with the protections and size of the diverse devices in the plant. Therefore, this section will address the Q capability of the plant, as compared with the requirements for the delivery of reactive power. The reference for this comparison is the curve representing the Q requirements as function of the voltage in the PoC, when the power plant is working at rated capacity (in this case, the plant is delivering 170 MW). Figure 4.1 represents this curve (which was already presented in Section 2.6.3) with the four most demanding points for the plant. The points are described as follows:

- **Point A.** The plant must be able to ”import” or ”absorb” up to 0.329 pu of reactive power, when the voltage at the PoC is 1.05 pu.
- **Point B.** The plant must be able to ”export” or ”inject” up to 0.329 pu of reactive power, when the voltage at the PoC is 1.04 pu.
- **Point C.** The plant must be able to ”export” or ”inject” up to 0.329 pu of reactive power, when the voltage at the PoC is 0.9 pu.
- **Point D.** the plant must be able to ”import” or ”absorb” up to 0.329 pu of reactive power, when the voltage at the PoC is 0.96 pu.

Points B and D are the most restrictive for the voltage constraint of the power converters of the grid. Recall from 2.3 that the converters are limited by the maximum and minimum voltage they can be exposed to without experiencing problems. Voltages over 1 pu limit the injection of reactive power, while voltages below 1 pu limit the absorption of reactive power. In normal operation, this is not an issue, since normally when there is an overvoltage in a bus, nearby generators need to absorb reactive power to bring the voltage back to 1 pu. Likewise, when the voltage in a bus is too low, nearby generators will inject reactive power to increase the voltage value back to 1 pu. However, this unfavorable situation is considered in the Technical Regulations, and therefore the plant needs to have the capability to act according to these requirements.

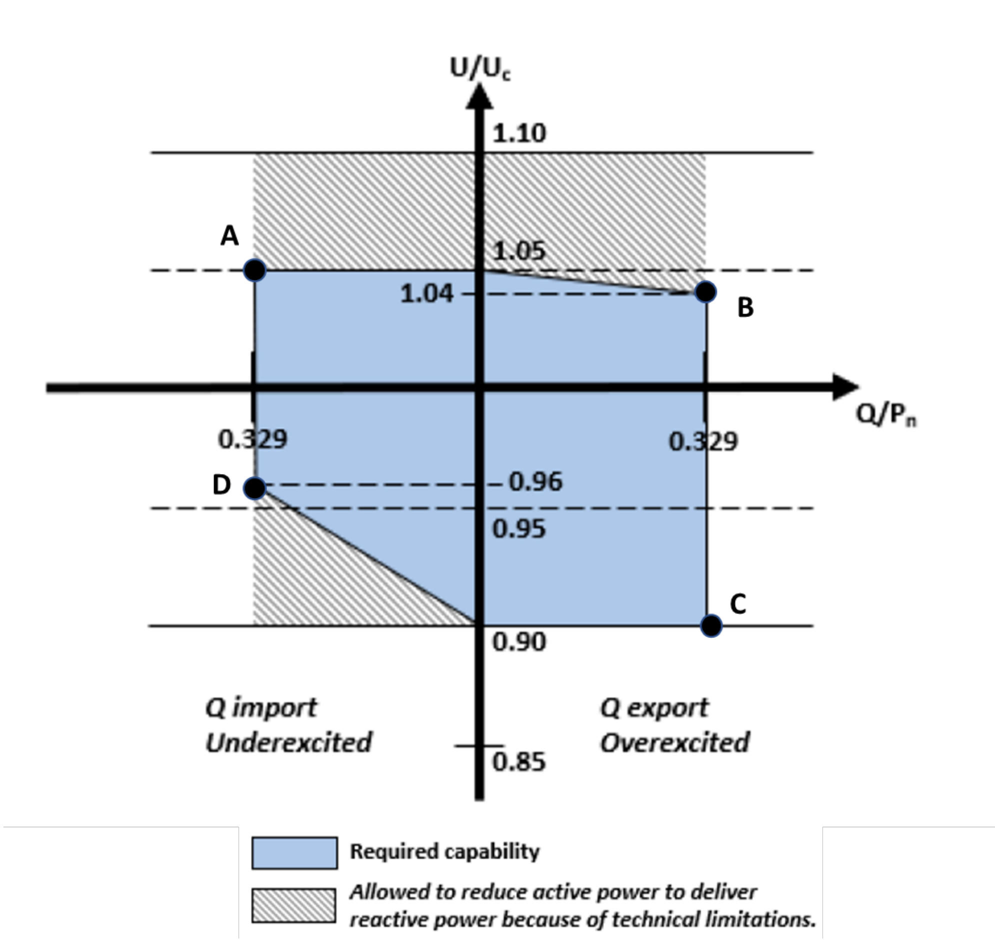

Figure 4.1: Requirements for the delivery of reactive power at P_{Nom} with 4 selected points. Adapted from [25].

The 3 Scenarios have been tested against these four set-points. To assess how much additional reactive power capacity is needed to meet such requirements, the plant is tested in each scenario first with zero capacity in the STATCOM. Then, in cases where the set-point is not achieved, the STATCOM capacity is increased in intervals of 5 MVAr, until the HPP Q capability is enough to meet the requirement.

In the following subsections, two tables present the most important parameters and resulting values of each simulation together with the appropriate discussion. The first table shows the balance of reactive power in the most relevant buses of the grid, as well as the reactive power consumed by the OLTC transformer and the export line. The second table presents the voltages in all the buses in the grid.

As the topology of the grid changes depending on the scenario, the nomenclature in each table is different. Nevertheless, a diagram illustrating each scenario has been attached to ease the understanding of the results.

All the values in the tables show the results without adding the STATCOM. The indicated STATCOM capacity on each scenario and point is such that the corresponding set-point is successfully achieved such capacity.

4.1.1 Scenario 1

Figure 4.2 presents the diagram of Scenario 1 to facilitate the interpretation of the results. Tables 4.1 and 4.2 show the Q balances and Voltage levels along the grid, respectively.

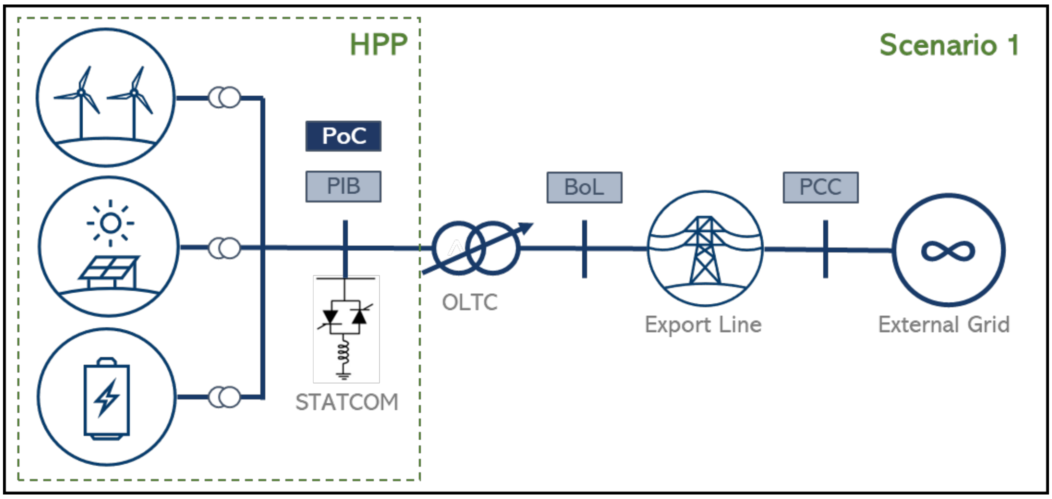

Figure 4.2: Diagram of Scenario 1. Own preparation.

In Scenario 1 the PoC is at the LV side of the OLTC transformer, so this is operated by the relevant TSO, and therefore it cannot be used to enhance reactive power capability by setting a favorable voltage level at the PIB. The results show that this configuration has problems to meet the Q requirements in Points B and D. This reveals that the voltage constraint of the converters is the main aspect limiting the plant's Q capability.

For Point B, the voltage level at the PoC is 1.04 pu, which drastically limits the injection capability of the plant. The result shows that a STATCOM of at least 15 MVAr needs to be installed to meet the grid code requirements at this point.

For Point D, something similar happens. The voltage level at the PoC is 0.96 pu, which restricts the absorption capability of the power plant. In this case the STATCOM needed is only 5 MVAr. The reason may be the fact that the minimum admissible voltage in the converters is 0.8 pu, so there is still an acceptable margin to consume Q. On the contrary, in point A since the maximum admissible voltage in the converters is 1.1 pu, the margin is smaller, and therefore the STATCOM capacity needed is larger.

Table 4.1: Scenario 1: Results of Reactive power Requirement test. Balance of Q.

Point	A	B	C	D
Q_{PoC} (MVAr)	-56.10	47.38	56.10	-54.84
Q_{PoC} (pu)	-0.33	0.28	0.33	-0.32
ΔQ_{trafo} (MVAr)	25.44	19.42	19.90	31.16
ΔQ_{line} (MVAr)	27.30	20.24	20.83	34.64
STATCOM (MVAr)	0.00	15.00	0.00	5.00

Table 4.2: Scenario 1: Results of Reactive power Requirement test. Voltage levels.

Point	A	B	C	D
V_{PoC} (pu)	1.05	1.039	0.936	0.954
V_{BoL} (pu)	1.001	1.040	1.027	0.902
V_{PCC} (pu)	1.078	1.012	0.991	0.997
Trafo ratio	36.5/132	32/132	29/132	37.5/132

4.1.2 Scenario 2

Figure 4.3 presents the diagram of Scenario 2 to facilitate the interpretation of the results. Tables 4.3 and 4.4 show the Q balances and Voltage levels along the grid, respectively.

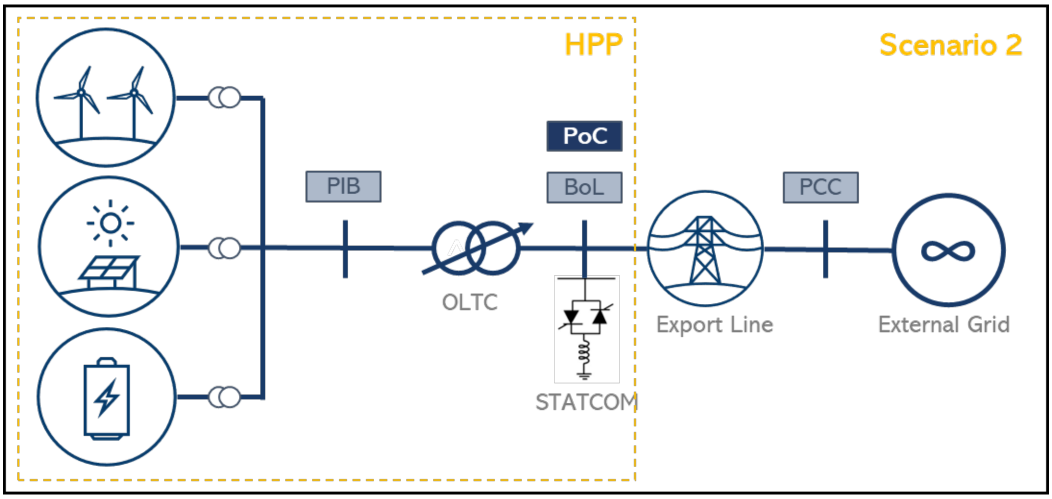

Figure 4.3: Diagram of Scenario 2. Own preparation.

In this Scenario the PoC is at the HV side of the OLTC transformer, meaning that the plant operators can use it to set a favorable voltage level at the PIB to enhance reactive power capability. Besides, as the highly reactive export line is behind the PoC, it is not detrimental for the achievement of the set-points.

The results show that in this configuration the reactive power capability of the individual power plants, optimized with the OLTC transformer, do not need additional reactive power sources to meet the grid code requirements in the most demanding cases.

Table 4.3: Scenario 2: Results of Reactive power Requirement test. Balance of Q.

Point	A	B	C	D
Q_{PIB} (MVAr)	-35.35	76.10	83.94	-31.34
ΔQ_{trafo} (MVAr)	20.75	20.00	26.12	24.76
Q_{PoC} (MVAr)	-56.10	56.10	57.80	-56.10
Q_{PoC} (pu)	-0.33	0.33	0.34	-0.33
ΔQ_{line} (MVAr)	21.52	20.97	29.10	26.90
STATCOM (MVAr)	0.00	0.00	0.00	0.00

Table 4.4: Scenario 2: Results of Reactive power Requirement test. Voltage levels.

Point	A	B	C	D
V_{PIB} (pu)	1.001	0.993	1.008	0.992
V_{PoC} (pu)	1.050	1.059	0.924	0.956
V_{PCC} (pu)	1.098	1.006	0.865	1.013
Trafo ratio	32.5/132	29.5/132	33.7/132	35.5/132

4.1.3 Scenario 3

Figure 4.4 presents the diagram of Scenario 3 to facilitate the interpretation of the results. Tables 4.5 and 4.6 show the Q balances and Voltage levels along the grid, respectively.

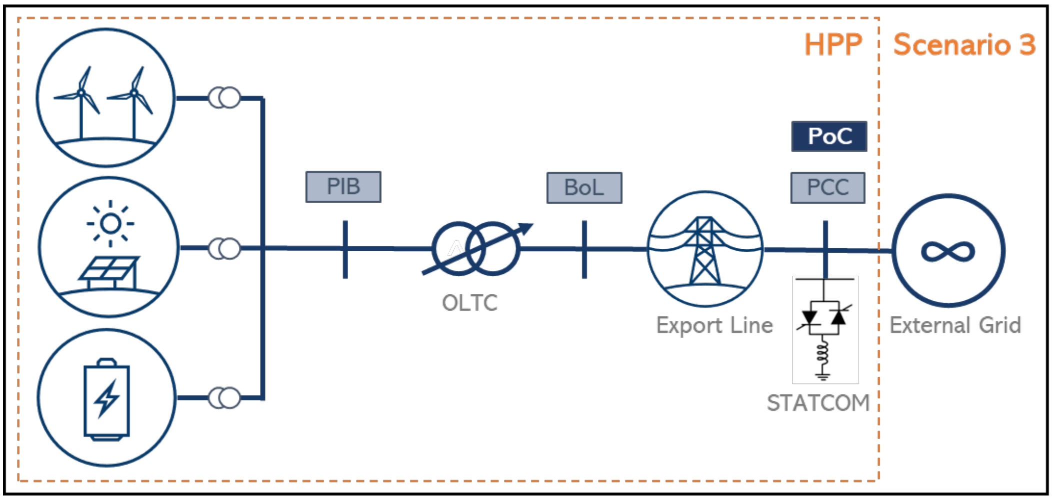

Figure 4.4: Diagram of Scenario 3. Own preparation.

In this scenario, the PoC happens to meet at the PCC, so it is at the end of the export line. This means that the plant operators have controllability over the OLTC transformer, but on the other hand the highly inductive export line will impact the injection capability of the HPP.

The results show that this configuration has issues when meeting the set-points given in points B and C. In this case, the voltage limitations are not a problem, since by making use of the OLTC transformer the voltage levels at the PIB are always close to 1 pu. This suggests that the current constraint of the converters is the main aspect limiting the plant's Q capability. The plant is working at rated capacity, meaning that there is already limited room for reactive power exchange with the grid. On top of this, both the line and the transformer are consuming between 20 and 25 MVArs each. The HPP needs to provide enough reactive power to compensate for this and still deliver the 0.329 pu at the PCC, but its current limitations prevent the injection of such amount of Q to the grid, so a STATCOM is needed. A STATCOM with a capacity of at least 25 MVArs is needed to meet the grid codes under this configuration.

For points A and D, where the set-point is an import of Q, the transformer and line actually enhance the absorption capability of the plant, so the specified references are achieved with no major difficulties.

Table 4.5: Scenario 3: Results of Reactive power Requirement test. Balance of Q.

Point	**A**	**B**	**C**	**D**
Q_{PIB} (MVAr)	-14.14	81.14	82.26	-5.64
ΔQ_{trafo} (MVAr)	20.48	19.21	24.12	23.78
ΔQ_{line} (MVAr)	21.48	19.88	26.48	26.68
Q_{PoC} (MVAr)	-56.10	41.99	31.99	-56.10
Q_{PoC} (pu)	-0.33	0.25	0.19	-0.33
STATCOM (MVAr)	0.00	20.00	25.00	0.00

Table 4.6: Scenario 3: Results of Reactive power Requirement test. Voltage levels.

Point	**A**	**B**	**C**	**D**
V_{PIB} (pu)	1.005	1.01	1.009	1.014
V_{BoL} (pu)	1.021	1.096	0.965	0.928
V_{PCC} (pu)	1.052	1.04	0.906	0.96
Trafo ratio	33/132	29/132	32.5/132	36.5/132

4.2 Voltage control function

This section presents the results when using the voltage control function to control the voltage at the PCC in the 3 different scenarios. For these results, the STATCOM capacity needed in each scenario (as per the results of Section 4.1) is included in the plant[1]. Two cases are studied in each Scenario. In Case 1, the starting voltage at the

[1]This is done by assuming that the previous section was a sizing optimization problem, where the smallest possible STATCOM was purchased to meet the grid code requirements. This section, on the

PCC is 1.1 pu, and Case 2 it is 0.9 pu. The idea is to test how closer the voltage at the PCC gets to 1 pu under each scenario to assess the performance on voltage control. In all cases the HPP is producing 0.7 pu of P (119 MW) and a droop of 4% has been used.

Having a droop value of 4% means that whenever the voltage level at PCC is above 1.04 pu or below 0.96 pu, the plant is absorbing or injecting the maximum value of reactive power allowed by its capability curve.

Starting from Case 1, all the Scenarios are within the voltage control ranges, since the voltage at the PCC is only $\sim 2.5\%$ over the nominal value. For this voltage value the droop-controller sets a total absorption of 106.25 MVAr to be distributed among the assets. For Scenarios 1 and 2 this is the total reactive power flow measured at the PIB. The only difference is how the overall reactive power set-point is distributed among the assets, since Scenario 2 does not have any STATCOM and therefore all the plants will have to absorb more Q as compared with Scenario 1.

For Scenario 3, this is the sum of the total reactive power flow measured at the PIB plus the reactive power consumed by the STATCOM, which is connected at the PCC. In this case, the export line and transformer contribute to decrease the voltage level at PCC back to its nominal value. Therefore, having the STATCOM at the beginning of the line (Scenarios 1 and 2) is preferable, since the current flowing through the cable is larger, and so are the reactive power consumed by the transformer and line. This explains why the voltage level achieved at Scenarios 1 and 2 is slightly better (0.001 pu) than in Scenario 3. Generally speaking, the Q absorption capability of the plant, together with the inductive character of the line and transformer, produce an effective response against overvoltages in all scenarios.

Regarding Case 2, Scenarios 1 and 2 are working outside their voltage ranges, as the voltage is beyond 0.96 pu. This means that the HPP is injecting as much Q as it can for this situation, as the assets are limited by the current constraints. Having the STATCOM, Scenario 1 is injecting more reactive power than Scenario 2, since its Q capability is enhanced. Therefore, a slightly higher voltage is achieved.

For Scenario 3, this case demonstrates the benefits of placing the STATCOM at the end of the line. As the plant needs to inject a vast amount of reactive power to the PCC, the transformer and export line weaken the HPP response by consuming an important part of this reactive power flow. Therefore, having the STATCOM at the end of the line, the total current flowing through the line and transformer is lower, and so are the Q values consumed by both. This leads to a voltage level of 0.965 pu at the PCC in Scenario 3, which is the only one working within its voltage ranges for this case.

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contrary, represents a situation during the operation of the plant, so the necessary equipment to meet the grid codes is considered to have been acquired previously.

Table 4.7: Case 1. Overvoltage in PCC. Results of all scenarios.

	Scen1	**Scen2**	**Scen3**
V_{PCC} (pu)	1.025	1.025	1.026
V_{PIB} (pu)	0.88	0.88	0.926
ΔQ_{trafo} (MVAr)	31.00	30.7	25.8
ΔQ_{line} (MVAr)	34.50	34.30	28.05
Q_{PIB} (MVAr)	-104.3	-104.6.0	-93.5

Table 4.8: Case 2. Undervoltage in PCC. Results of all scenarios.

	Scen1	**Scen2**	**Scen3**
V_{PCC} (pu)	0.952	0.950	0.965
V_{PIB} (pu)	1.000	0.99	0.978
ΔQ_{trafo} (MVAr)	16.7	16.09	16.6
ΔQ_{line} (MVAr)	17.19	16.6	16.96
Q_{PIB} (MVAr)	121.12	115.6	124.6

5 Conclusion and future works

This project has developed a novel control architecture to control the reactive power exchanged between an HPP and the power grid based on external set-points provided by the relevant TSO or DSO. The control system is based on a hierarchical architecture, as found in the literature, and it includes two control functions: reactive power control and voltage control. These are two of the three different control functions indicated by the Danish Technical Regulations applied to PPM and, therefore, to an HPP combining wind, solar and storage assets[1].

The reactive power control function has been used to assess whether the HPP meets the requirements for reactive power capability indicated in the Grid Codes, while the voltage control function has been tested in two cases: with voltage levels 10% above and below nominal values.

Another objectives of the project was to explore different configurations of the ownership of the line and the to find the optimal placement and size of reactive power support devices such as a STATCOM. This objective has been achieved by using 3 different scenarios, each of which represents a different degree of ownership of the export line and transformer. The transformer connecting the HPP with the export line is an OLTC transformer, and its impact in enhancing the reactive power capability of the plant has also been analyzed.

The results show that being able to control the OLTC transformer increases the reactive power capability of the power plant, as this device can help to maintain internal voltage levels in the HPP close to 1 pu, thus reducing the influence of converter voltage limitations on the capability of the plant. It must be noted, though, that generally speaking, if the owner of the transformer is the TSO or DSO, they would normally control the voltage at the PoC and fix it to 1 pu. So, in normal conditions, there may be not much added value in owning the OLTC transformer. However, to meet the grid code requirements, controlling the OLTC can be very beneficial: the results show that with no ownership of the OLTC, a STATCOM of 15 MVAr (this is 8.8% of the nominal capacity of the HPP) needs to be added in order to comply with the most demanding set-points. Having controllability on the OLTC, however, no additional STATCOM is needed.

When owning the export line, the injection capability of the HPP is limited, because HV overhead lines are very inductive, and therefore they tend to absorb large amounts of reactive power in normal operating conditions. So, the plant needs to supply all the reactive power that the lines and the OLTC transformer absorb. The results are aligned with this idea, since the resulting capacity to be added in this scenario has a similar value than what the line absorbs (around 25 MVAr). On the other hand, the absorption capability is enhanced, so no added capacity is needed to meet the ”import” set-points.

[1] This is an assumption made in the project.

In general, for the scenario where the OLTC is owned by a third party, converter voltage limitations are more restrictive; while for the scenario where the export line is part of the HPP, converter current limitations are more restrictive instead.

Regarding voltage control, the ownership of the OLTC seems to not play a decisive role[2], since the performance of both scenarios 1 and 2 is very similar. However, if the export line is owned and, therefore, the STATCOM can be placed at the end of the line, the injection capability is enhanced, and therefore the voltage controllability at the PCC in front of undervoltages is improved. This is what the results show, as when owning the line the voltage level achieved at the PCC is closer to 1 than in the other two scenarios. Nevertheless, for the case of overvoltage all the scenarios behave in a similar way.

As very little studies dedicated to voltage control in HPPs have been found in the literature, this project humbly helps to establish the bases of coordinated reactive power and voltage control architecture in HPPs. Therefore, there are still many aspects of this topic that need further attention, opening the door to future works. Some of them are listed below:

- **Improving the accuracy of the data.** As the main objective of this project was to develop a novel control architecture, not too much resources have been used to obtain very accurate data for the power plants. The numbers for a WPP were taken and generalized for the other plants (using all values in pu). Therefore, there may be value in replicating this study but taking a particular topology of the power plants involved and calculating the equivalent impedances that impact the reactive power capability of the HPP.
- **Improving the dispatch algorithm.** The dispatch algorithm here implemented distributes reactive power references according to the availability of each asset. This is straightforward to implement and works properly, but another dispatch strategy could probably make a better use of the assets. Maybe a novel dispatch algorithm for reactive power in HPPs could be developed which is inspired in the dispatch algorithms used to optimize power flows along the transmission and distribution systems.
- **Including the OLTC in the control system.** Due to technical difficulties and having other priorities, the control of the OLTC transformer has been excluded from the voltage control loop. Including it and automating the tap-changer can also add value to the model and reveal interesting conclusions in the future.
- **Enable Fault Ride Through.** FRT has been also excluded from the control systems here developed because this project focused on static simulations, so faults and imbalances were out of the scope of the study. Therefore, integrating a FRT function together with the existing control architecture can provide interesting insights to the dynamic behavior of an HPP. In general, exploring the dynamic

[2]As long as a third-party owner makes sure that the voltage at PoC is always close to 1 pu.

performance of this control architecture is left to do and opens several research opportunities.

- **Running simulations with low active power generation.** In situations where the export line is loaded below its Surge Impedance Loading value, it behaves as a capacitor rather than as an inductor (which is the common case). All the simulations carried out here assume a generation of active power of either 1 pu or 0.7 pu, so this situation has not been studied[3]. Therefore, performing simulations under these conditions to analyze the behavior of the plant with very light loading of the line can provide a broader picture of the performance of the HPP.

[3]due to timing issues.

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